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Commercial Jet Transport Crashworthiness

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Seattle, Washington

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FOREWORD

The Transport Crashworthiness Study was conducted under NASA Contract No. NAS1-16076 funded jointly by NASA and the FAA. Technical Monitors for this contract were L. Vosteen and R.G. Thomson of the Langley Research Center and C.A. Caiafa of the FAA Technical Center. E. Widmayer was Principal Investigator, assisted by O.B. Brende of Airworthiness Safety.

D.L. Parks of Crew Systems and D.W. Twigg of Boeing Computer Services made significant contributions to section 5, Current State of Crashworthiness Technology, and contributed all of appendix D. Ray E. Horton of the Advanced Composites Development program contributed section 4.4. a part of section 4.0, titled, Advanced Materials. K. H. Dickenson was the Program Manager. The study was conducted under the supervision of W.W. Bingham, head of Structures Research Division of Structures Technology.

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COMMERCIAL JET TRANSPORT CRASHWORTHINESS

EDWARD WIDMAYER, JR. AND OTTO B. BRENDE

Boeing Commercial Airplane Company

1.0 SUMMARY

This report presents the results of a study to identify areas of research and approaches that may result in improved occupant survivability and crashworthiness of transport aircraft. This study was jointly sponsored by National Aeronautics and Space Agency (NASA) and the Federal Aviation Administration (FAA). The thrust of the study is the definition of areas of structural crashworthiness for transport aircraft which might form the basis for a NASA/FAA Research Program.

NASA and the FAA are planning a 10-year research and development program to improve the structural impact resistance of general aviation and commercial jet transport aircraft. As part of this program parallel studies have been conducted by The Lockheed California Company, The Douglas Aircraft Company, and The Boeing Commercial Airplane Company to review the accident experience of commercial transport aircraft, assess the accident performance of structural components and the status of impact resistance technology, and recommend areas of research and development for that 10-year plan. This report gives the results of the Boeing study.

2.0 INTRODUCTION

The scope of the study from the contractual statement of work is:

"A study to define approaches to improve the crashworthiness of transport aircraft is described in this statement of work. Aircraft accident data and current aircraft design practices will be used to define a range of crash conditions that might form the basis for developing crashworthiness design technology. In addition, analytical and/or experimental techniques required to determine the adequacy of crashworthy design features will be defined and the adequacy of existing methods and techniques will be evaluated. While meeting the specific objectives of this study, consideration should be given to the increasing role advanced composite materials might play in the design of future transports.

Resume of tasks: .

1. To review and evaluate transport aircraft accident data to define a range of crash situations that may form the basis for developing improved crashworthiness design technology.

2. Identify structural components and aircraft systems that significantly participate in or influence the crash dynamic behavior of an aircraft in the scenarios defined in 1.

3. To define areas of research and approaches for improving crashworthiness.

4. To identify test techniques, test data, analytical methods, etc. needed to evaluate the crash dynamic response of transport aircraft."

BACKGROUND

Safety is the primary consideration in the design and operation of commercial transport aircraft. For over 40 years the FAA with its predecessor the Civil Aeronautics Administration (CAA), NASA and its predecessor National Advisory Committee for Aeronautics (NACA), the National Transportation Safety Board (NTSB), the airlines, unions, the manufacturers and other foreign government agencies have contributed to the development and advancement of safety in commercial aviation. Their efforts have resulted in the Federal Aviation Regulations (FAR) which define the minimum standards for safety. These regulations are continually reviewed to ascertain the adequacy of the standards. This concern is reflected in the safety record of air carriers jet aircraft operations over the past 20 years. Figure 2.1 shows that the accident rate for all types of accidents has declined to about 2.5 per million departures.

The continuing concern for safety at Boeing has placed an emphasis on determining the cause of accidents and evaluating the crashworthiness of aircraft structure and systems. Because of this emphasis, safety related design changes and improvements, based on operational experience and accident data, are continually being evaluated and often incorporated in new design aircraft and in-service aircraft.

However, the initial conditions of an accident and the subsequent responses of the aircraft are complex phenomena and it is difficult to quantify the level of structural crashworthiness of a specific design or to compare one design to another. For design improvements, the crash environment is known only in general terms.

Current technology is based on the best available knowledge obtained from accident surveys, some complete aircraft crash tests, seat/occupant tests, and from military and automotive programs

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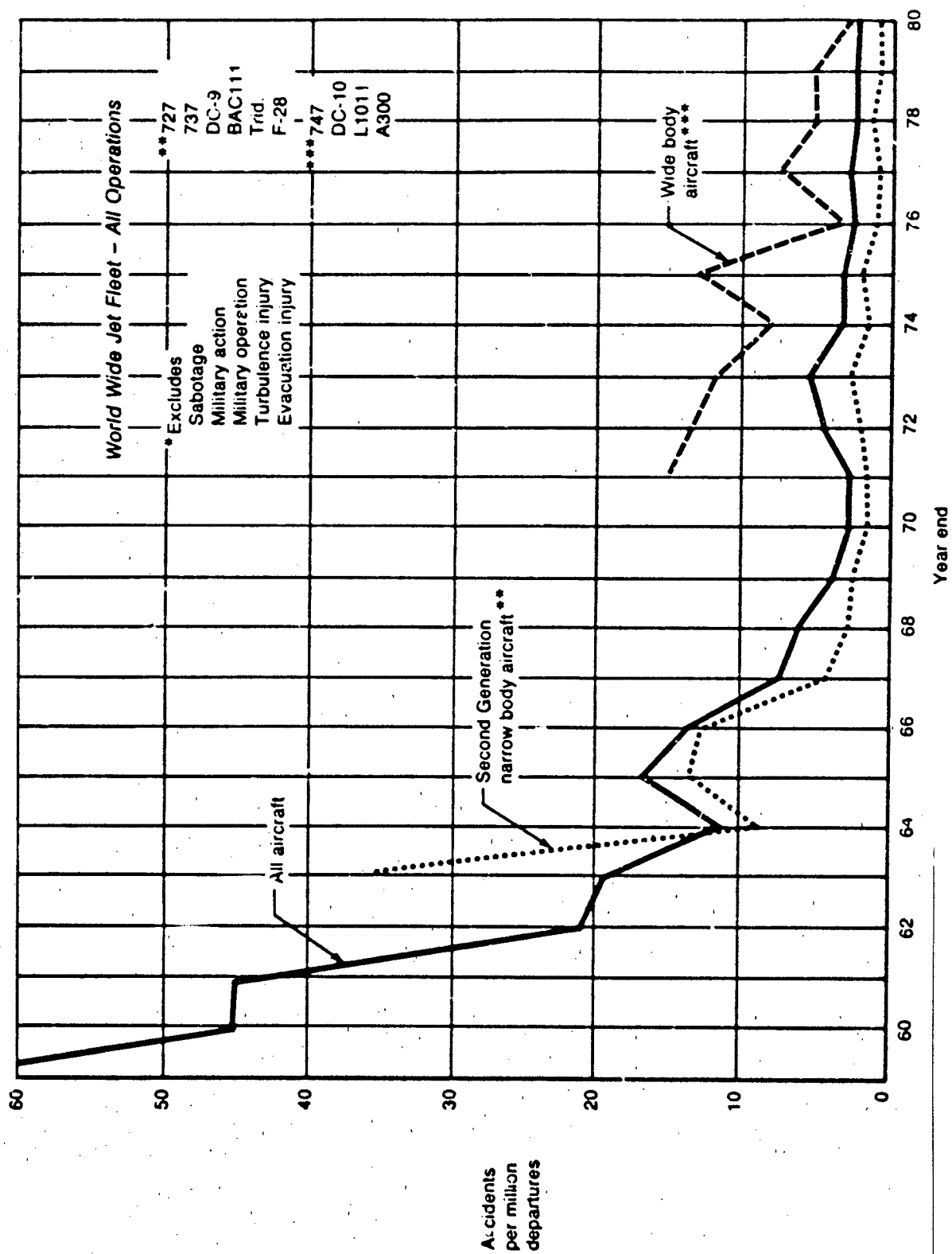
Figure 2.1–Accident Rates for All Types of Accidents *

aimed at specific problems. Each manufacturer of aircraft has developed empirical engineering practices that treat structural crashworthiness. These practices while producing good products, are extremely limited in application.

Some analytical tools have been developed for modeling the nonlinear response of occupants in seats and of aircraft structures. These tools have constraints due to lack of computing power and have had limited validation and application. This in turn has limited the development of technical approaches to crash modeling and simulation. Further, it is not established that these tools include all the technology necessary to adequately treat the complete structural crashworthiness problem.

With regard to facilities and methods for testing for crashworthiness, some facilities are currently available or under development. Some test methods have been developed by the FAA, NASA, and the U.S. Army for seats, components, and general aviation aircraft and helicopters. Full-scale aircraft crash test methods are being extended by the FAA and NASA.

The Boeing study under this contract is limited to commercial jet transport aircraft. This is the area of Boeing Commercial Airplane Company expertise and conforms to the company product line. It also reflects the structure of the world fleet. The world transport fleet as of 1980 consisted of 75.7% jet aircraft, 15.7% turboprop aircraft, 8% piston engined aircraft and 0.5% helicopters. Aircraft on order are divided 9 to 1 towards jet aircraft. This implies that the percentage of jet aircraft in the fleet will increase during the time frame of the potential NASA/FAA research program.

While the recommendations for research arising in this study are directed towards technology for commercial jet transports there is an applicability to the general and private aviation sectors as well. Development of analytical methods, test techniques and facilities also have applicability to military aircraft and the automotive industry.

REPORT ORGANIZATION

The main sections of the report are Accident Data Review and Scenario Identification, Role of Structural Components in Crashworthiness, Current State of Crashworthiness Technology, and Conclusions and Recommendations. Accident Data Review and Scenario Identification discuss sources and selection of accidents, various categories of the data, accident scenario development, and ranges of impact conditions for the scenarios. The Role of Structural Components in Crashworthiness treats the participation of structural components, accident severity and survivability, interaction of components, problem areas for advanced materials in structural components. The Current State of Crashworthiness Technology considers the U.S. Army's Aircraft Crash Survival Design Guide, occupant modeling and human impact tolerance, structural modeling and test technology, assesses the technology and discusses research to improve the technology. Conclusions and Recommendations presents areas for research and development to be included in the NASA/FAA 10-year General Aviation and Commercial Transport Aircraft Crashworthiness.

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3.0 ACCIDENT DATA REVIEW AND SCENARIO IDENTIFICATION

A review and evaluation of accident data has been made for the years 1959—1979 which cover the commercial jet transport worldwide operations for aircraft certified under Federal Aviation Regulations (FAR), Part 25. The total accident base has been reviewed, and potentially survivable accidents have been selected for further analysis.

These accidents have been categorized with respect to airplane size, configuration, crash environment, operational condition, cause of accident, injuries, structural damage, and fire hazard. These categories are discussed and the level of engineering data in accident reports is assessed.

Three basic crash scenarios have been developed from the sequence of events observed in the accidents. These scenarios have been divided further into subsets to account for variations between accidents within a scenario. The range of initial conditions for each subset has been established. These scenarios may serve as a starting point for research on crashworthiness, but require further refinement to reflect current accident experience.

BOEING ACCIDENT FILE AND STUDY DATA BASE

The Boeing file of aircraft accidents and incidents is limited to all known commercial jet aircraft occurrences involving worldwide aircarrier operation since 1959. For research, study, and analysis purposes, a selected group of these accidents form a "statistical data bank" of 583 occurrences that include all operations from 1959 through 1979. Excluded from this statistical data bank are occurrences that involve factors beyond the control of the airframe manufacturer such as sabotage, military action, military operations, turbulence injury, and evacuation injury (unless caused by a hardware deficiency).

Accident data have been obtained from various sources. FAA/CAB reports and NTSB reports of U.S. aircarrier accidents, have been used extensively. While the early reports (circa 1960) contained, for the most part, sparse details on structural factors and on the cause of injury/fatalities, the later reports are much more complete. Human Factors Factual Reports prepared by the NTSB are particularly useful with respect to the sequence of events, cause of injury/fatalities, performance of cabin interior equipment and egress factors. Containing somewhat less data are the International Civil Aviation Organization of the United Nations (ICAO) released accident reports of both U.S. and foreign aircarrier occurrences. Other sources of accident information include the British Air Registration Board, Airline Pilots Association, and airline reports, official accident reports released by foreign governments, periodicals and newspaper accounts, and the Boeing Company files. The Boeing data base is summarized in figure 3.1.

The relationship between fatalities and hull loss is shown in figure 3.2. Here it may be seen that of the 275 hull losses, 206 involved fatalities and the three fatal injury accidents involved substantial damage to the aircraft.

The percentage of accidents by operational phase and by operational time is shown in figure 3.3. Considering those operational phases taking place near or on the ground, 79.3% of the accidents occur in 18% of the operational time. Further, those accidents that occur during climb, cruise, and descent are generally nonsurvivable and outside the range of this study.

583 total accidents* of all types	
147	involved U.S. carrier domestic operations
40	involved U.S. carrier international operations
28	involved U.S. carrier test and training operations
42	involved U.S. carrier non-scheduled and cargo operations
72	involved foreign carrier domestic operations
168	involved foreign carrier international operations
43	involved foreign carrier test and training operations
43	involved foreign carrier non-scheduled and cargo operations
Of these operational accidents	
275	resulted in hull loss
214	involved fatalities of passengers and/or crew on board the commercial jet aircraft.

*Excludes:
    Turbulence (injury)
    Emergency evacuation (injury)
    Sabotage
    Military action/military operations

Note: excludes 33 non-operational hull losses
and 15 sabotage or military action hull losses.

Figure 3.1–Accidents During Twenty Years of Jet Operations

All operations* 1959-1979

*Excludes:
Emergency evacuation (injury)
Sabotage
Military action
Turbulence (4 accidents involved a fatal injury)

275 hull loss

206 fatal

5 fatal injury accidents with no A/C damage

281 substantial damage

3 fatal injury accidents with A/C subs. damage

22 serious injury accidents with no or minor A/C damage

583

100   200   300   400   500   600

0

Number of accidents
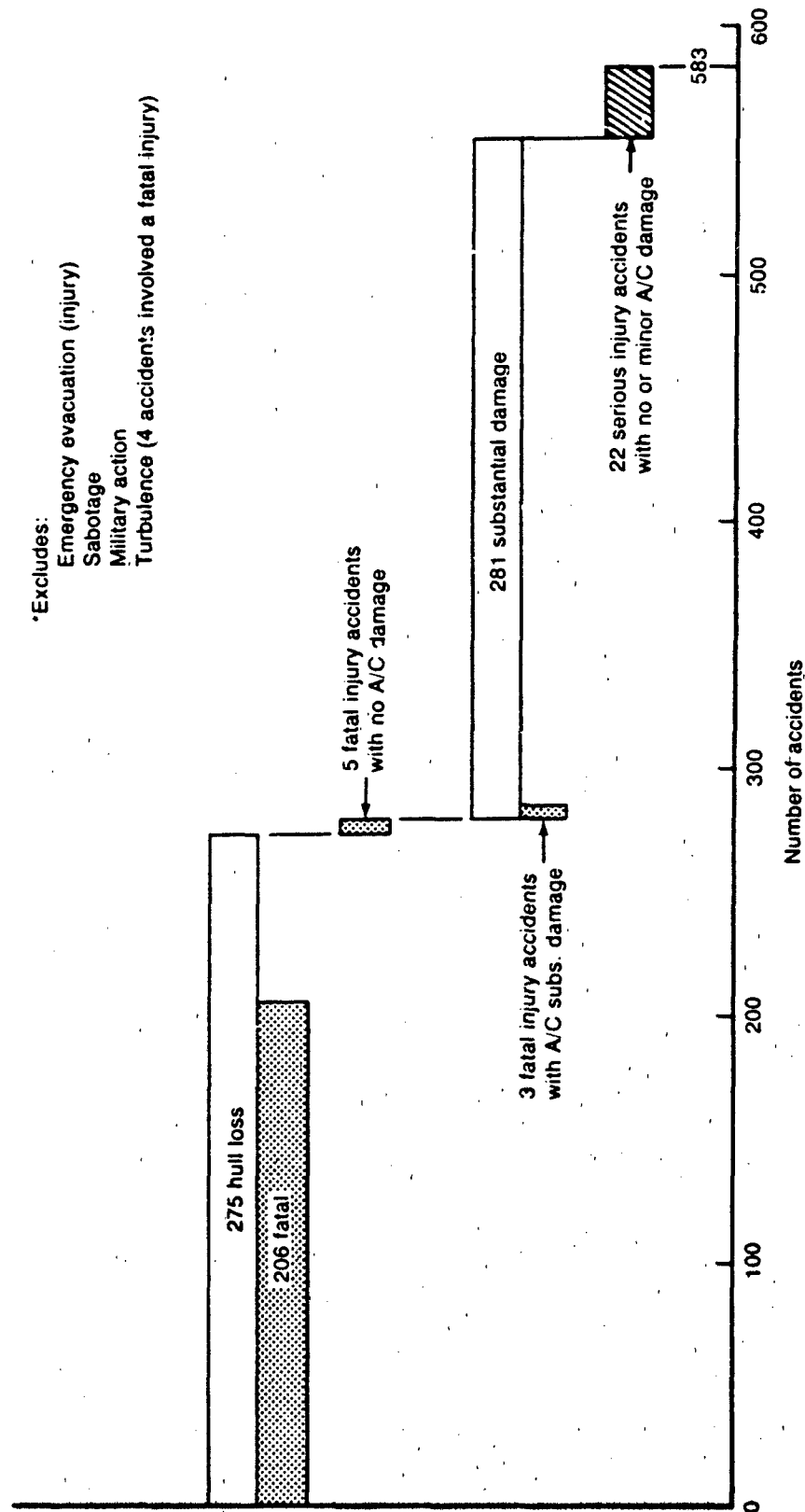
Figure 3.2–Relationship Between Fatalities and Hull Loss

All types of accidents* – world wide jet fleet 1959-1979

*Excludes:
    Turbulence (injury)
    Emerg evacuation (injury)
    Sabotage
    Military action

Profile based on:
    3,000 hours/year
    8.2 hours/day
    5 flights/day

Percent of accidents

| Load, taxi, etc. 3.3% | Takeoff 12.4 | Initial climb 9.1% | Climb 6.5% | Cruise 5.8% | Descent 8.4% | Initial aprch 7.0% | Final aprch 26.6% | Landing 20.9% |

54.5%

Holding pattern

Takeoff runway

Nav fix

Outer marker

Flare point

Runway

| 2% | 2% | 2% | 8% | 64% | 10% | 10% | 2% | 2% | 2% |

14%

Exposure – percent of operational time
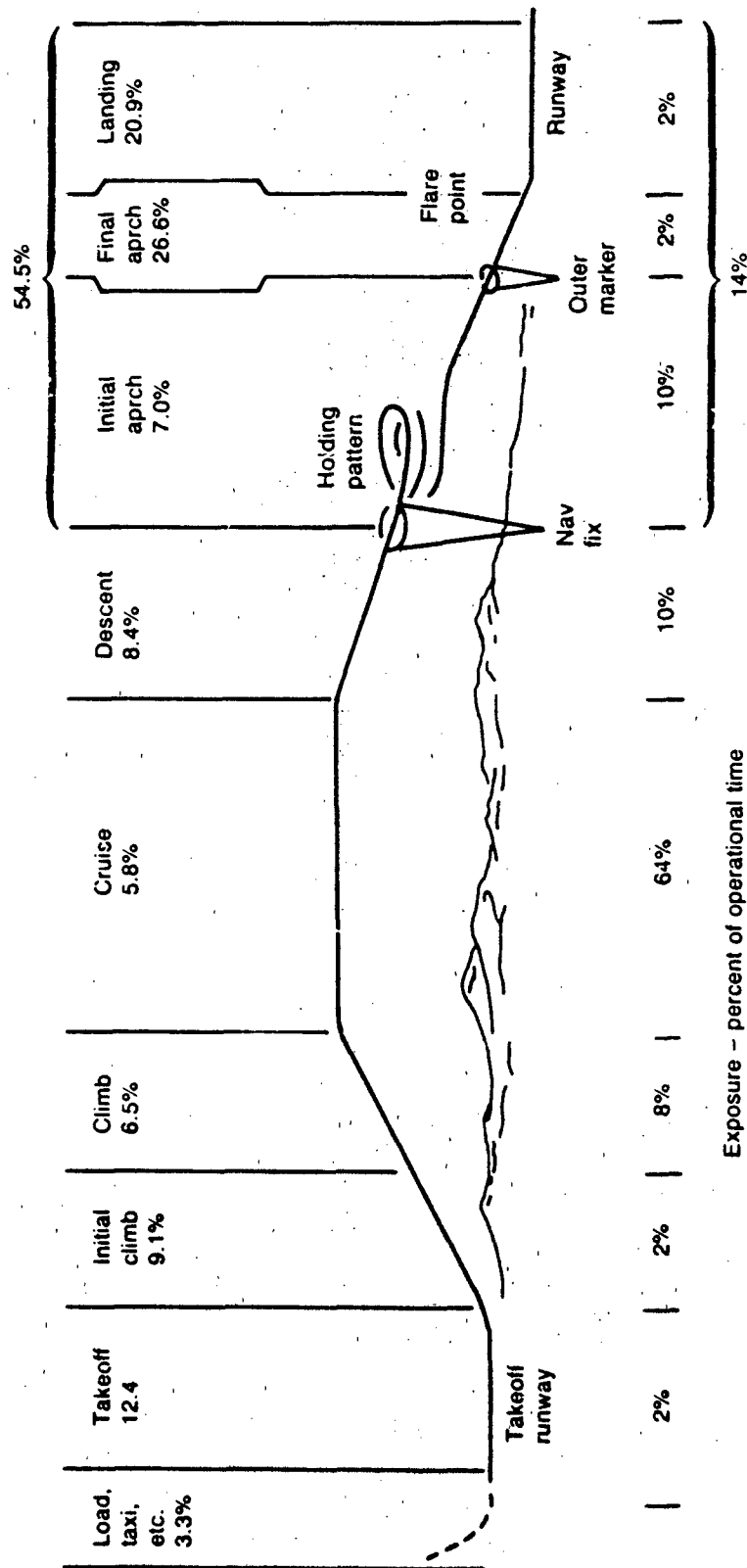
Figure 3.3–Percentage of Accidents by Operational Phase and Operational Time

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STUDY DATA BASE

A study data base was formed from the accident data base. At least one of the following criteria must exist for consideration in the study:

1. Airframe survivable volume maintained (prior to severe fire)

2. At least one occupant did not die from trauma

3. Potential for egress present

4. Accident demonstrates structural or system performance

It should be noted that criterion (2) is significantly more severe than the FAR criterion (see app. D, fig. 3.5) or NTSB definitions (see app. A) of a survivable accident. Criterion (2) does not mean that if one survives all should survive, rather that one occupant was able to withstand this accident environment in his immediate vicinity. This permits accidents to be considered for research definition and direction that are beyond the scope of current design criteria.

Using the above criteria, about 400 accidents were selected from the total data base of 583. These 400 were then subject to an in-depth review and many were eliminated from further consideration because no injury occurred and/or the aircraft was structurally crashworthy to that level of crash environment. Other accidents were eliminated because the injury was due to human behavior rather than other factors. Following this preliminary review a list of approximately 200 "candidate accidents" was selected for detailed review. These accidents were deemed to have the potential for a reduction in injuries/fatalities if some increase in crashworthiness were provided, or that demonstrated significant crash performance of the structure. For these 200 accidents, data forms (see app. B) were completed to the extent of the available data.

Detailed reviews of these 200 cases resulted in additional eliminations and a final list of 153 accidents for this study (see fig. 2.1). These accidents are designated as "potentially survivable" throughout the report. The selected list was checked against the injury and hull loss lists of the Boeing data base to ensure completeness. Appendix C gives a list of accidents for 1980 for future consideration.

It should be noted that the inclusion of the less severe accidents might alter any statistics derived from the data base. Consequently, care is required in comparing the results of this study to studies using other data bases. However, comparisons to other studies indicate that all of the known severe potentially survivable accidents involving commercial jet transports have been included in the study data base.

The data base does not represent the complete distribution of possible accidents in the statistical sense. There are probably types of accidents that might happen in the future that are not represented. The accident data base does not represent a stationary random process. Certain types of accidents that occurred during the jet introduction period are not seen in the mature stage. This could have an important impact on the selection of scenarios for future design consideration. Evidence of this maturity is seen in figure 2.1 by the marked decrease in the accident rate with time. Further, care must be exercised in predictions of future occurrences from the past.

A summary of the selected study data base is presented in table 3.1. As may be seen, 87% of the cases involve hull loss and 78% of the cases involve fatalities or serious injury, while fire occurred in 67% of the cases. Fatalities due to fire were present in 37% of the cases, fatalities due to trauma

Table 3.1–Data Base Summary

	Cases	%
Total accidents	153	100.0
Foreign	91	59.5
U.S. and possessions	62	40.5
Hull loss	133	87
Fatalities or serious injury	119	73
Fire	103	67
Fire caused fatalities	57	37
Trauma caused fatalities	55	36
Drowning	10	6.5
Special	4	2.6

were present in 36% of the cases, and fatalities due to drowning were present in 6% of the cases. The selected cases clearly represent serious accidents.

The 707 accident in Tahiti, in which there was one survivor, has not been included in the data base because the aircraft was not recovered and the survivor could not supply any details as to what happened. Four special cases are included in the data base. The first special case is the 707 in London in 1968 where the aircraft caught fire on takeoff and made a successful landing but five deaths occurred during evacuation due to fire. The second special case is the DC-8 at Toronto in 1970 where the aircraft was damaged during an attempted landing and exploded during the subsequent attempted go-around killing the 108 occupants. The third special case is the DC-9 in Boston in 1973 where the aircraft struck a seawall, broke up and burned, but one passenger walked out of the fire but died within 24 hours. The fourth special case is the 737 Madras accident on April 26, 1979, in which the detonation of an explosive device in the forward lavatory led to landing conditions that resulted in an overrun.

The study data base is presented in table 3.2. Accidents are listed by date (month, day, year), aircraft type, and location of the accident. Hull loss is indicated by x with a blank indicating substantial damage. Number of occupants, fatalities, and serious injuries are also shown. Flight phase (takeoff, initial climb, approach, landing, taxi) and the presence of fire are indicated.

Accidents have been assessed as impact survivable (YES) if no deaths were attributed to trauma. Accidents have been assessed as partially impact survivable (PAR) if some deaths were attributed to trauma but there were some deaths attributed directly to fire related causes or there were survivors. Those accidents in which there were some survivors but the cause of fatalities was not determined have been labelled as undefined (UDF).

CATEGORIZATION OF THE ACCIDENT DATA

PROBABLE CAUSE OF ACCIDENTS

The probable cause of the accidents is presented in figure 3.4. "Probable cause" is based on the determination of the accident investigation body. For 13 accidents the cause is unknown. For 140 cases where cause has been determined, 78.6% of the cases are attributed to the cockpit crew, 11.4% to the airplane, 5% to weather, 2.2% to the airport/air traffic controller, 1.4% to miscellaneous, 0.7% to maintenance, and 0.7% to sabotage.

The aircraft was the cause of the accident in 11.4% of the cases. Landing gear systems and support structure were involved in seven accidents. Failures involved brakes, wheels, tires, and structure. Engine disintegration, thrust loss, and thrust reversers were involved in six accidents. Flight instrumentation was involved in two accidents and ground spoilers and elevator trim tab were involved in one accident each.

From these data it may be concluded that about 89% of the accidents might have been avoided by improved pilot assistance and ground control. The most significant improvements in safety may be obtained through accident avoidance. Such items as ground proximity warning, wind shear detection, automated landing and navigation systems, and advanced integrated systems for pilot assistance offer the best hope for eliminating most accidents in the "avoidable" category.

Improved ground control and reduction of hazards on and around airports is another area for improved safety. The avoidance of collisions between aircraft and with ground vehicles should be attainable. Reduction of hazards such as drainage ditches, poles, trees, columns, outbuildings, and birds from airports is a matter of concern. In addition the short/overrun areas for runways could be improved to reduce the severity of accidents in these areas.

Table 3.2–Study Data Base.

	HULL LOSS	ONBOARD	FATAL	SERIOUS INJURY	FLIGHT PHASE	FIRE	IMPACT SURVIVABLE	WATER LANDING
101959 707 OSO, WASHINGTON	X	8	4	0	APP	FIRE	PAR	WAT
082759 CMT ASCUNCION	X	50	2	?	APP		UDF	
022060 CMT BUENOS AIRES	X	6	0	0	LDG	FIRE	YES	
071161 DC8 DENVER	X	122	17	0	LDG	FIRE	YES	
011961 DC8 JFK	X	106	4	?	TO	FIRE	PAR	
061561 707 LISBON		103	0	2	LDG	FIRE	YES	
122161 CMT ANKARA	X	34	27	6	CLI	FIRE	UDF	
092461 720 BOSTON		71	0	2	LDG		YES	WAT
092761 CVL BRASSILA	X	?	?	?	LDG	FIRE	UDF	
072761 707 HAMBURG	X	41	0	10	TO	FIRE	YES	
060362 707 PARIS, ORLY	X	132	130	2	TO	FIRE	UDF	
082062 DC8 RIO DE JANIERO	X	105	15	?	TO		YES	WAT
070363 CVL CORDOBA, ARGENTINA	X	70	0	?	APP	FIRE	YES	
031864 BAC WISLEY, ENG.		5	0	1	LDG		YES	
040764 707 JFK	X	145	0	7	LDG		YES	WAT
112364 707 ROME	X	73	48	20	TO	FIRE	YES	
032264 CMT SINGAPORE	X	86	0	0	LDG	FIRE	YES	
050265 720 CAIRO	X	127	121	6	APP	FIRE	UDF	
070165 707 KANSAS CITY	X	66	0	2	LDG		YES	
110865 727 CINCINNATI	X	62	58	4	APP	FIRE	PAR	
111165 727 SALT LAKE CITY	X	91	43	35	LDG	FIRE	YES	
091365 880 KANSAS CITY	X	4	0	0	CLI	FIRE	YES	
022765 880 IKI IS., JAPAN	X	6	0	2	LDG	FIRE	YES	
070466 DC8 AUCKLAND	X	5	2	1	TO	FIRE	PAR	
082666 880 TOKYO	X	5	5	0	TO	FIRE	YES	
030466 DC8 TOKYO	X	71	64	8	APP	FIRE	UDF	
063066 TRI KUWAIT	X	83	0	0	APP		YES	
122466 DC8 MEXICO CITY	X	110	0	6	APP	FIRE	YES	
021566 CVL NEW DELHI	X	81	2	14	APP	FIRE	YES	
110667 707 CINCINNATI	X	36	1	2	TO	FIRE	PAR	
112067 880 CINCINNATI	X	82	70	12	APP	FIRE	PAR	
030567 DC8 MONROVIA	X	90	51	23	APP	FIRE	UDF	
063067 CVL HONG KONG	X	80	17	5	APP		YES	WAT
092967 CMT ROME	X	66	0	0	LDG		YES	
110567 880 HONG KONG	X	137	1	?	TO		YES	WAT
122768 DC9 SIOUX CITY	X	66	0	3	TO		YES	
032868 DC8 ATLANTIC CITY	X	4	0	2	LDG	FIRE	YES	
061368 707 CALCUTTA	X	63	6	2	APP	FIRE	YES	
060368 727 JFK		102	0	4	LDG		UDF	
032168 727 CHICAGO	X	3	0	1	TO	FIRE	YES	
020768 707 VANCOUVER, B.C.	X	61	1	0	LDG		PAR	
021668 727 TAIPEI	X	63	21	42	APP	FIRE	UDF	
040868 707 LONDON	X	127	5	?	CLI	FIRE	YES	
042068 707 WINDHOEK	X	128	123	5	CLI	FIRE	PAR	
080268 DC8 MILAN	X	95	12	?	APP	FIRE	YES	
011469 BAC MILAN	X	33	0	0	TO		YES	
101669 DC8 STOCKTON, CA.	X	5	0	0	LDG	FIRE	YES	
010569 727 LONDON GATWICK	X	65	50	14	APP	FIRE	PAR	
011369 DC8 LOS ANGELES	X	45	15	17	APP		YES	WAT
092169 727 MEXICO CITY	X	118	28	78	APP		PAR	WAT
091269 BAC MANILA	X	47	45	2	APP	FIRE	PAR	

Table 3.2–Study Data Base (Continued)

Date	A/C	Location	HULL LOSS	ONBOARD	FATAL	SERIOUS INJURY	FLIGHT PHASE	FIRE	IMPACT SURVIVABLE	WATER LANDING
062469	880	MOSES LAKE	X	5	3	?	CLI	FIRE	YES	
021170	707	STOCKTON, CA		6	0	1	LDG		YES	
071970	737	PHILADELPHIA	X	62	0	1	TO		YES	
090870	DC9	LOUISVILLE		94	0	0	LDG	FIRE	YES	
122870	727	ST. THOMAS	X	55	2	11	LDG	FIRE	YES	
080870	990	ACAPULCO	X	8	0	8	LDG	FIRE	YES	
112770	DC8	ANCHORAGE	X	229	47	47	TO	FIRE	YES	
072770	DC8	NAHA, OKINAWA	X	4	4	0	APP		PAR	WAT
020970	CMT	MUNICH	X	23	0	0	TO	FIRE	YES	
033170	CVL	CASABLANCA	X	82	61	21	APP	FIRE	UDF	
050270	DC9	ST. CROIX, V.I.	X	63	25	25	LDG		PAR	WAT
070570	DC8	TORONTO	X	108	108	0	LDG	FIRE	YES	
091570	DC8	JFK	X	156	0	11	LDG	FIRE	YES	
010570	990	STOCKHOLM	X	10	5	4	CLI		PAR	
071970	BAC	GERONA, SPAIN	X	85	0	3	TO		YES	
120770	BAC	CONSTANA	X	27	18	?	APP		UDF	
113070	707	TEL AVIV	X	3	0	0	TO	FIRE	YES	
012371	707	BOMBAY	X	5	0	0	TO	FIRE	YES	
090671	BAC	HAMBURG	X	121	22	?	CLI	FIRE	UDF	
121571	707	URUNCHI, CHINA	X	3	0	0	LDG		YES	
051872	DC9	FT. LAUDERDALE	X	10	0	3	LDG	FIRE	YES	
092472	DC8	BOMBAY	X	120	0	0	LDG	FIRE	YES	
120872	737	CHICAGO MIDWAY	X	61	43	12	APP	FIRE	PAR	
121572	747	MIAMI	X	160	0	0	LDG		YES	
122072	DC9	CHICAGO O'HARE	X	45	10	9	TO	FIRE	YES	
122972	L10	MIAMI	X	176	99	60	APP	FIRE	NO	WAT
012172	DC9	ADANA	X	5	1	?	APP	FIRE	UDF	
041772	VC1	ADDIS ABABA	X	107	43	?	TO	FIRE	UDF	
081372	707	JFK		186	0	0	TO	FIRE	YES	
112872	DC8	MOSCOW, USSR	X	76	61	15	CLI	FIRE	UDF	
122372	F28	OSLO	X	45	40	?	APP	FIRE	UDF	
122872	F28	BOLBAO, SPAIN	X	4	0	4	LDG		YES	
030573	707	DENVER		3	0	0	TO	FIRE	YES	
073173	DC9	BOSTON, MASS.	X	89	89	0	APP	FIRE	PAR	
112773	DC9	CHATTANOOGA	X	77	0	5	APP	FIRE	YES	
112773	DC9	AKRON, OHIO	X	26	0	16	LDG		YES	
012273	707	KHANO, NIGERIA	X	202	172	?	LDG	FIRE	YES	
053173	737	NEW DELHI	X	65	52	?	APP	FIRE	YES	
060973	707	RIO DE JANEIRO	X	4	2	0	APP		PAR	WAT
102873	737	GREENSBURO		96	0	0	LDG	FIRE	YES	
061673	707	BUENOS AIRES		86	0	0	LDG	FIRE	YES	
062373	DC8	JFK		128	0	8	LDG	FIRE	YES	
121773	DC9	GREENSBORO		91	0	0	TO	FIRE	YES	
121773	DC1	BOSTON	X	151	0	3	LDG	FIRE	YES	
121973	707	NEW DELHI	X	109	0	3	LDG	FIRE	YES	
122373	CVL	MANAUS, BRAZIL	X	57	0	1	LDG		YES	
011674	707	LOS ANGELES	X	63	0	3	LDG	FIRE	YES	
011374	707	PAGO PAGO, AM. SAMOA	X	101	97	5	APP	FIRE	YES	
091174	DC9	CHARLOTTE, N.C.	X	82	71	10	APP	FIRE	PAR	
091174	727	PORTO ALEGRE, BRAZIL		74	0	0	LDG		YES	
010174	F28	TURIN, ITALY	X	42	38	4	APP	FIRE	UDF	

Table 3.2—Study Data Base (concluded)

	HULL LOSS	ONBOARD	FATAL	SERIOUS INJURY	FLIGHT PHASE	FIRE	IMPACT SURVIVABLE	WATER LANDING
010274 F28 IZMIR, TURKEY	X	72	65	7	CLI	FIRE	UDF	
031574 CVL TEHRAN, IRAN	X	96	15	?	TAX	FIRE	YES	
112074 747 NAIROBI, KENYA	X	157	59	44	CLI	FIRE	PAR	
020975 BAC LAKE TAHOE	X	44	0	0	TO		YES	
033175 737 CASPER, WYO.	X	99	0	1	LDG		YES	
062475 727 JFK	X	124	112	12	APP	FIRE	PAR	
080775 727 DENVER	X	134	0	15	CLI		YES	
092475 F28 PALEMBANG	X	62	25	?	LDG	FIRE	UDF	
111275 727 RALEIGH, N.C.		139	0	1	APP		YES	
111275 DC1 JFK	X	139	0	2	TO	FIRE	YES	
111575 F28 NR. BUENOS AIRES	X	66	0	0	APP		YES	
121675 747 ANCHORAGE		121	0	2	TAX		YES	
010276 DC1 ISTANBUL	X	373	0	1	LDG	FIRE	YES	
040576 727 KETCHIKAN	X	57	1	32	LDG	FIRE	YES	
042276 720 BARRANQUILLA, COL.	X	4	0	1	APP	FIRE	YES	
042776 727 ST. THOMAS, V.I.	X	88	37	19	LDG	FIRE	PAR	
062376 DC9 PHILADELPHIA	X	105	0	36	LDG		YES	
121676 880 MIAMI	X	3	0	1	TO		YES	
111676 DC9 DENVER	X	85	0	2	TO	FIRE	YES	
030477 DC8 NIAMEY, NIGER	X	4	2	2	APP	FIRE	YES	
031777 707 PRESTWICK	X	4	0	0	TO	FIRE	YES	
032777 747 TENERIFE	X	396	334	62	TAX	FIRE	PAR	
032777 747 TENERIFE	X	246	246	0	TO	FIRE	YES	
040477 DC9 NEW HOPE, GA.	X	85	62	22	APP	FIRE	PAR	
092777 DC8 KUALA LUMPUR	X	79	34	?	APP	FIRE	UDF	
100277 DC8 SHANNON	X	259	0	1	TO	FIRE	YES	
111977 727 MADEIRA	X	164	128	36	LDG	FIRE	PAR	WAT
112177 BAC BARILOCHE, ARG.	X	79	45	34	APP		UDF	
121877 CVL MADEIRA	X	57	36	13	LDG		YES	WAT
041877 DC8 TOKYO	X	140	0	0	TO		YES	
111777 747 JFK		3	0	0	LDG		YES	
021178 737 CRANBROOK, B.C.	X	49	42	5	LCG	FIRE	PAR	
030178 DC1 LOS ANGELES	X	197	2	31	TO	FIRE	YES	
030378 DC8 SANTIAGO DE COMPO.	X	222	0	52	LDG		YES	
040278 737 SAO PAULO	X	42	0	0	LDG	FIRE	YES	
040478 737 CHARLROI, BELGIUM	X	3	0	0	LDG	FIRE	YES	
050878 727 PENSACOLA	X	58	3	11	APP		YES	WAT
052578 880 MIAMI	X	6	0	0	TO		YES	
062678 DC9 TORONTO	X	107	2	?	TO		PAR	
070978 BAC ROCHESTER		77	0	1	LDG		YES	
103179 DC1 MEXICO CITY	X	87	70	17	LDG	FIRE	UDF	
111578 DC8 COLUMBO, SRI LANKA	X	259	195	?	APP	FIRE	UDF	
121778 737 HYDERABAD, INDIA	X	126	1	4	TO	FIRE	YES	
122378 DC9 PALERMO, ITALY	X	129	108	?	LDG		UDF	WAT
122978 DC8 PORTLAND, OREGON	X	186	10	23	APP		PAR	
032578 720 LONDON		82	0	?	LDG		YES	
020979 DC9 MIAMI	X	5	0	1	CLI		YES	
021979 707 ST. LUCIA		170	0	0	APP		YES	
031479 727 DOHA,QATAR	X	64	45	15	APP	FIRE	PAR	
042579 737 MADRAS	X	67	0	8	LDG	FIRE	YES	
100779 DC8 ATHENS	X	154	14	0	LDG	FIRE	YES	

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Selected impact survivable accidents
all operation 1959-1979 world wide air carriers

Probable cause	Number of accidents	Percent of accidents with known causes
Cockpit crew	110	78.6%
Airplane	16	11.4%
Weather	7	5.0%
Airport/Atc.	3	2.2%
Misc.	2	1.4%
Maint.	1	0.7%
Sabotage	1	0.7%
Total Unknown	140 13	
Total	153	
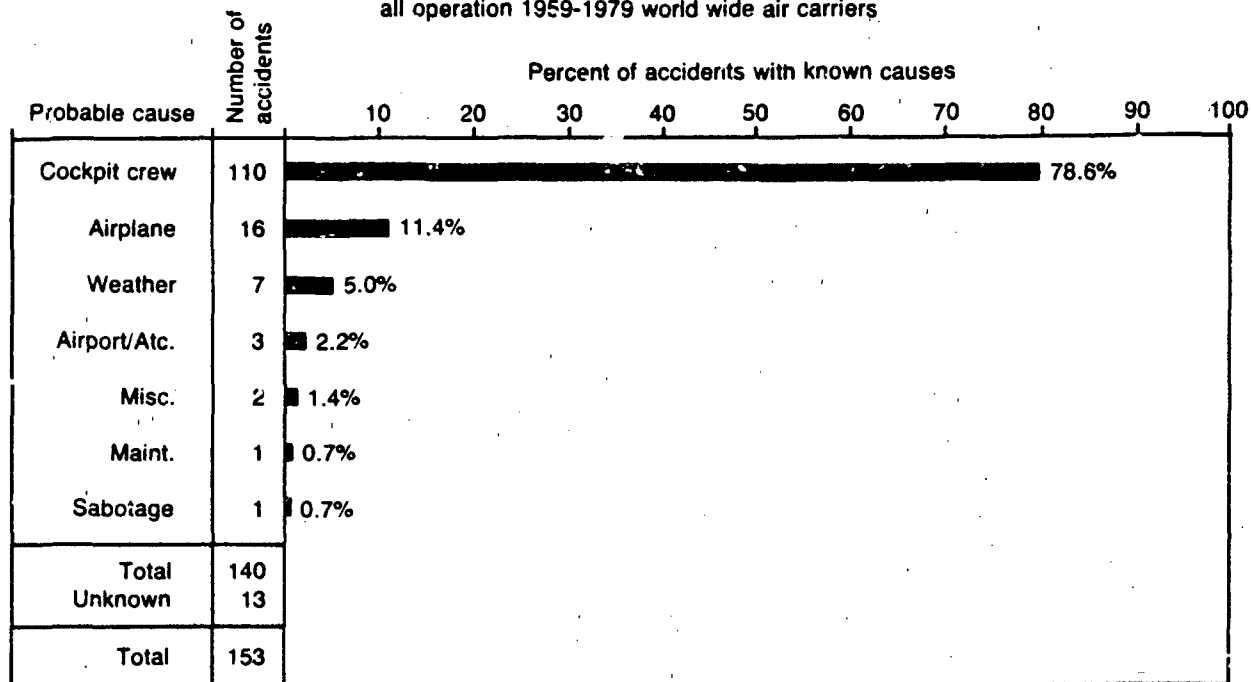
Figure 3.4 – Probable Cause of Accidents

AIRCRAFT SIZE

Accident cases were categorized with respect to size as measured by gross weight. The 737, DC-9, Comet IV, BAC-111, Trident, F28 and Caravelle form a short haul group up to 72.5 tonnes. The 720, 727, 880, and 990 are included in the 72.5 to 113 tonnes short haul group. The 707 and the DC-8 are in the 113 to 158 tonnes narrow-body long haul group. Wide-body aircraft such as the L-1011, DC-10, and the 747 are in the over 158-tonne wide-body long haul group.

Referring to figure 3.5, it may be seen that each size group is represented in the data base. Smaller short haul aircraft constitute approximately 40% of the cases, larger short haul group approximately 20% of the cases, narrow-body long haul group approximately 35% and wide-body long haul aircraft approximately 5%.

Of particular interest is the effect of size on aircraft crash performance and survivability. Considering the effects of scale as in dynamic modeling, it might be expected that larger aircraft would fare better than smaller aircraft if the crash environment is not scaled up. Further, the individual occupant does not scale up, but becomes relatively smaller in the larger aircraft with a corresponding improvement in his survival prospects. For instance, fuselage structural elements such as frames and stringers are stronger in an absolute sense and offer greater energy absorbing capability for larger commercial jet aircraft than for smaller propeller-driven aircraft. This feature provides an inherent crashworthiness to the jet as compared to the propeller aircraft.

A qualitative assessment of the accident data seems to indicate that relative size within the jet group has only minor effects on the crash performance of commercial jet transports. In general, it takes a larger tree, a larger house, and a deeper or wider ditch to do equivalent damage to a large aircraft. Since no two accidents are identical, an accurate comparison of damage between a large and small jet airframe cannot be made.

There is some indication that there may be some effect of size between some smaller propeller-driven transport aircraft and the current jet fleet. Three accidents not included in the study data base were reviewed that involve high wing propeller-driven aircraft of one generic type. In these accidents the seat response was different from that observed in survivable jet aircraft accidents in that many seats separated. Further, there were instances of seat "stacking" in the forward fuselage and seat ejection on a large scale. These propeller-driven aircraft while smaller than the jet aircraft were certified to the FAR 9 g longitudinal deceleration requirement. But, because of dimensional and structural arrangement differences these smaller aircraft present a higher impedance to the seats than do the larger jet aircraft. This may account for the different seat crash response as seen by the two types of aircraft.

AIRCRAFT CONFIGURATION

Accident cases were categorized with respect to configuration. Emphasis was placed on differences between aircraft types and service uses. The aircraft fuselage internal configuration was classified according to type of service, i.e. passenger or nonpassenger. Also in the internal fuselage configuration is the presence of body fuel cells and body fuel lines. The external configuration differences are related to fuselage width, engine placement, landing gear, and fuel cells.

Referring to figure 3.5, it may be seen that approximately 20% involve nonpassenger service. Nonpassenger service was further divided into cargo, training, and positioning flights.

Regarding cargo service, a review of the accident data shows some cases where cargo shift during the accident increased the hazard to the flight crew. A notable instance is the Miami 880 accident on December 16, 1976 where cattle pens broke loose during an overrun and blocked the cockpit door.
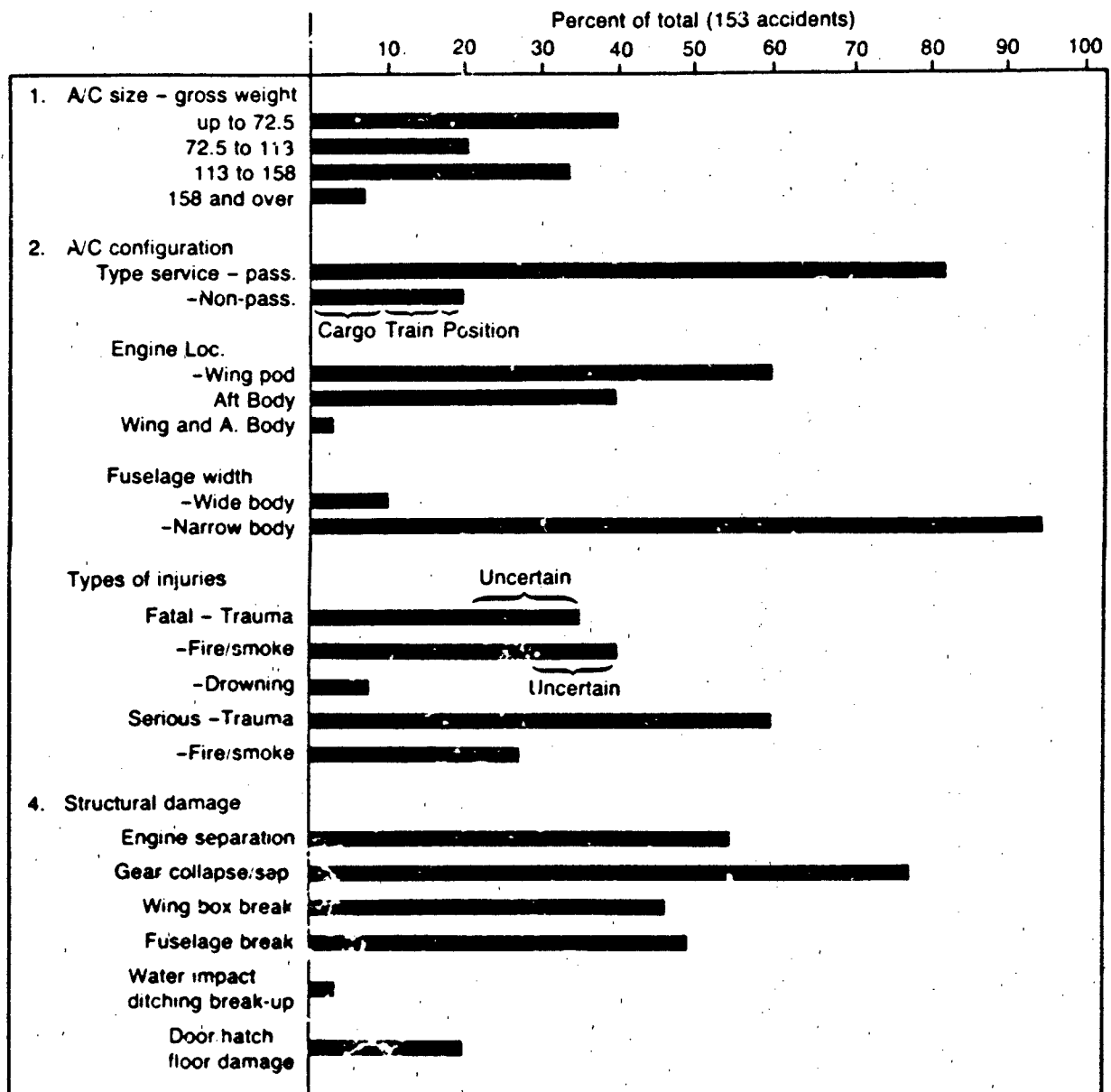
Figure 3.5—Accident Data Categories

Figure 3.5 - Accident Data Catagories (Concluded)

Training accidents most frequently involve engine-out takeoff attempts. These accidents involve extreme yaw and roll angles with ground strikes of wings, engines or aft fuselage. Some accidents involve touch-and-go landing practice.

The principal variation in structural configuration is in placement of engines. Approximately 60% of the accidents involve aircraft with wing mounted engines and 37% involve aft mounted engines, while 3% involve wing and aft body mounted engines. The aft mounted engines only separated from the aircraft due to high acceleration loading, while the wing/pylon mounted engines separated both from high accelerations and from contact with external objects. The Comet IV has engines mounted internally in the wings which contained the engines in a crash.

Engine placement was observed to affect the fire hazard. Associated with the aft body location is the breaking of engine fuel lines and also of body fuel lines. The wing pylon mounted location had in addition to fuel line breaks, the rupturing of wing fuel tanks due to pylon/engine separation. Fires occurred in engines internally mounted in the wing.

The wide-body long haul aircraft have main body landing gear in addition to the wing mounted gear. Here the crash response was to transfer high impact loads to the fuselage structure.

With regard to fuel cells, the Comet IV has wing pod tanks. These tanks have separated due to high accelerations and have contacted external objects. The associated fire hazard was tank rupture.

TYPES OF INJURIES

The data base contains 119 accidents or 67% involving fatalities and/or serious injury. For this study the NTSB definitions (see app. A) have been extended further to identify the cause of the fatality/injury. Trauma is taken to mean that the fatality/injury is caused by mechanical forces such as inertia forces resulting from high accelerations or from impact with the surrounding structure. Fire/smoke is assigned to those fatalities/injuries that result from burns, inhalation of hot gases, smoke or noxious fumes. In some cases, passengers are presumed to have received trauma injuries that prevented or slowed down their egress and as a result they died of smoke or flames. For those accidents where the aircraft stopped in water, fatalities due to drowning are identified. No attempt has been made to identify injuries (chemical burns) due to contact with raw fuel although some instances have occurred in both land and water accidents.

Referring to figure 3.5, it may be seen that approximately 35% of the accidents involve fatalities due to trauma, 37% involve fire/smoke, and 6% involve drowning. With respect to the serious injuries, 60% involve trauma, and 30% involve fire/smoke. It should be noted that some accidents may involve combinations of the above causes of injury.

OPERATIONAL PHASE

Five operational phases were used for grouping the accidents. These are takeoff, climb, approach, landing, and taxi. Referring to figure 3.5, it may be seen that takeoff involved 22.5%, climb involved 7.9%, approach involved 30.5%, landing involved 37.1% and taxi involved 2.0% of the accident cases.

The groupings by operational phase are given in table 3.3 with a brief description of the accident. From these data, the complexity of the accidents may be observed. While frequently there are common factors between accidents, when the details are considered each accident is a separate event.

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Table 3.3—Accidents by Operational Phase

(a) Takeoff
(b) Climb
(c) Approach
(d) Landing
(e) Taxi

(a) Takeoff

			Hull Loss	Onboard	Fatal	Serious Injury	Flight Phase	Fire	Impact Survivable	Water Landing	Description
011961	DCR	JFK	X	106	4	?	TO	FIRE	PAR		ABORTED AT V1-OVERRAN-HIT BLAST FENCE-CROSSED BLVD-KILLED FLT DECK CREW
022761	707	HAMBURG	X	41	0	10	TO	FIRE	YES		VEERED OFF RUNWAY-SEPARATED GEAR. #2 & #3 ENG. BROKE FUSE-FIRE BOTH WINGS
060362	707	PARIS, ORLY	X	132	130	2	TO	FIRE	UDF		OVERRUN-BRAKE FIRE-LMG SEP.-FIRE LT WING-RMG SEP.-#2 END SEP.-TWR, BLG
042362	DC8	RIO DE JANIERO	X	105	15	?	TO		YES	WAT	ABORTED-OVERRUN-LOST THRUST REVERSERS-HIT FENCE, ROAD-ENTER WATER-DROWNINGS
112364	707	ROME	X	73	48	20	TO	FIRE	YES		ABORTED-VEERED OFF RUNWAY-HIT STREAM ROLLER AND LOST #4 ENG-FUEL FIRE, EXPLOSION
070466	DC8	AUCKLAND	X	5	2	1	TO	FIRE	PAR		ENGINE OUT TRAINING-RT. WING HIT GRD-A/C BROKE UP
082666	880	TOKYO	X	5	5	2	TO	FIRE	YES		ENGINE OUT TRAINING-VEERED OFF RUNWAY-HIT DITCH-LOST GEAR, ENGINES-WING FIRE
110667	707	CINCINNATI	X	36	1	2	TO	FIRE	PAR		ABORTED AT V1-OVERRAN-LOST MAIN GEAR-A/C DAMAGED IN SLIDE OUT-WING BREAK-FIRE
110567	880	HONG KONG	X	137	1	?	TO		YES	WAT	ABORT-VEERED OFF RUNWAY INTO BAY-FUSELAGE BROKE & SANK-DROWNING
122764	DC9	SIOUX CITY	X	66	0	3	TO		YES		ABORTED AT V1-SLIDE OFF RUNWAY INTO TREES
032168	727	CHICAGO	X	3	0	1	TO	FIRE	YES		ABORTED AT VR-OVERRAN-HIT DITCH-BROKE LT. WING, FUSELAGE-#4 ENG. SEP.
011469	BAC	MILAN	X	33	0	0	TO		YES		LOST POWER AT VR-WHEELS UP LDG.-SLID INTO TREES
071970	737	PHILADELPHIA	X	62	0	1	TO		YES		LOST POWER-OVERRAN-GEAR FAILED. #1 ENG. SEP, #1 TANK RUPTURED
112770	DC3	ANCHORAGE	X	229	47	47	TO	FIRE	YES		ABORTED-HIT DITCH AND ANTENNA TOWER-A/C LOST PARTS-FUSE. BROKE-FIRE
020970	CNT	MUNICH	X	23	0	0	TO	FIRE	YES		ABORTED-HIT FENCE-GEAR SEP.-FIRE IN RT. WING
071970	BAC	GERONA, SPAIN	X	85	0	3	TO		YES		ABORTED-OVERRAN-HIT 20 FT. HIGH EMBANKMENT
113070	707	TEL AVIV	X	3	0	0	TO	FIRE	YES		HIT A/C UNDER TOW-LOST ENGINES AND GEAR IN SLIDE OUT
012371	707	BOMBAY	X	5	0	0	TO	FIRE	YES		ENGINE OUT TRAINING-LOST POWER-TAIL HIT RUNWAY-VEERED INTO ROUGH TERRAIN
122072	DC9	CHICAGO O'HARE	X	45	10	9	TO	FIRE	YES		HIT CV880-IMPACTED RUNWAY-SKIDDED 800 FT.-FIRE IN RUPTURED FUEL LINES
041772	VC1	ADDIS ABABA	X	107	43	7	TO	FIRE	UDF		LOST POWER-ABORTED-OVERRAN- OVER STEEP BANK-HIT ILS TOWER-IMPACTED GRD.
081372	707	JFK	X	186	0	0	TO	FIRE	YES		ABORTED-OVERRAN-HIT BLAST FENCE-BROKE LEFT WING-FIRE
030573	707	DENVER	X	3	0	0	TO	FIRE	YES		3 ENG FERRY FLT-LT WING HIT GRD-A/C VEERED OFF RUNWAY
121773	DC9	GREENSBORO	X	91	0	0	TO	FIRE	YES		LOST POWER-ABORTED-VEERED OFF RUNWAY-LMG FOLDED-LT WING TANK RUPTURED
020975	BAC	LAKE TAHOE	X	44	0	2	TO		YES		HIT SNOW BANK-VEERED OFF RUNWAY-RT WING, RMG, NG SEPARATED
111275	DC1	JFK	X	139	0	0	TO	FIRE	YES		ENGINE DISINTEGRATED-ABORTED-FIRE #3 ENG-MENT OFF TAXIWAY-RT WING LOST FUEL
121676	880	MIAMI	X	3	0	1	TO		YES		FWD CG-ABORTED-OVERRUN-STOPPED IN CANAL
111676	DC9	DENVER	X	85	0	2	TO	FIRE	YES		STALL AT VR-ABORTED-VEERED OFF RUNWAY-HIT DITCHES AND POLES-TANK RUPTURE
031777	707	PRESTWICK	X	4	0	0	TO	FIRE	YES		ENGINE OUT TRAINING-LARGE YAW & ROLL-A/C HIT GRD-SLID OUT LOSING GEAR & ENGINE
032777	747	TENERIFE	X	246	246	0	TO	FIRE	YES		A/C HIT PAA 747-LOST LMC AND #2 ENG.-HIT RUNWAY AND BURNED
100277	DC8	SHANNON	X	259	0	1	TO	FIRE	YES		WHEEL FAILURE-ABORTED-RT MAIN TANK PUNCTURE-FUEL FED FIRE
041877	DC8	TOKYO	X	140	0	0	TO		YES		VEERED OFF RUNWAY-LOST ALL GEAR AND ENGINES
030178	DC1	LOS ANGELES	X	197	2	31	TO	FIRE	YES		ABORTED AT V1-OVERRUN-LMG SEP., RUPTURED TANKS
052578	880	MIAMI	X	6	0	0	TO		YES		FWD G.C. PROBLEM-A/C OVERRUN AND BROKE UP
062678	DC9	TORONTO	X	107	2	?	TO		PAR		LOST POWER-OVERRAN-CRASHED INTO 51 FT DEEP RAVINE
121778	737	HYDERABAD, INDIA	X	126	1	4	TO	FIRE	YES		A/C STALLED-ABORTED WHEELS UP-SEPARATED BOTH ENG-FIRE STARTED LT WING

N= 35

Table 3.3–Accidents by Operational Phase (Continued)

(a) Takeoff
(b) Climb
(c) Approach
(d) Landing
(e) Taxi

(b) Climb

		HULL LOSS	ONBOARD FATAL	SERIOUS INJURY	FLIGHT PHASE	FIRE	IMPACT SURVIVABLE	WATER LANDING	DESCRIPTION
122161 CMT	ANKARA	X	34	27	6	CLI	FIRE	UDF	STALL-HARD IMPACT FROM 450 FT. ALTITUDE
091365 R80	KANSAS CITY	X	4	0	0	CLI	FIRE	YES	STALL-HARD IMPACT-4G OUT TRAINING
040668 707	LONDON	X	127	5	?	CLI	FIRE	YES	#2 ENG DISINTEGRATE-LOST #2,-FIRE-FAILED TO SHUT OFF FUEL VALVE-FIRE DEATHS
042068 707	WINDHOEK	X	128	123	5	CLI	FIRE	PAR	#2 FLEW INTO GRD-FUSELAGE BORKE-6 SURVIVORS BEHIND COCKPIT
062469 880	MOSES LAKE	X	5	3	?	CLI	FIRE	YES	ENGINE OUT-TRAINING-A/C HIT ON RT. WING-SLID 2000 FT.-FIRE
010570 990	STOCKHOLM	X	10	5	4	CLI		PAR	3 ENG FERRY FLIGHT-IMPACT TREES,GRD WITH WING-FUSELAGE AFT OF COCKPIT DESTROYED
C90671 BAC	HAMBURG	X	121	22	7	CLI	FIRE	UDF	LOST ALL POWER AT 165 FT-STEEP BANK-CRASHED ON AUTOBAN-HIT BRIDGE
112872 DC8	MOSCOW, USSR	X	76	62	15	CLI	FIRE	UDF	STALL DUE TO FLAP RETRACTION
C10274 F28	IZMIR, TURKEY	X	72	65	7	CLI	FIRE	UDF	AT 33 FT BANKED LEFT AND CRASHED-PROBABLY STALL
112074 747	NAIROBI, KENYA	X	157	59	44	CLI	FIRE	PAR	NOSE HIGH STALL-AFT FUSELAGE HIT ELEVATED ROAD-A/C BROKE UP
080775 727	DENVER	X	134	0	15	CLI		YES	WIND SHEAR-STALL
020979 DC9	MIAMI	X	5	0	1	CLI		YES	ENG OUT TRAINING-WING HIT GRD

N: 12

Table 3.3–Accidents by Operational Phase (Continued)

(c) Approach

Date	Type	Location	HULL LOSS	ONBOARD	FATAL	SERIOUS INJURY	FLIGHT PHASE	FIRE	IMPACT SURVIVABLE	WATER LANDING	DESCRIPTION
101959	707	OSO, WASHINGTON	X	8	4	0	APP	FIRE	PAR	WAT	ATTEMPTED CRASH LDG IN RIVER-HIT TREES-FWD FUSELAGE DESTROYED
087759	CMT	ASUNCION	X	50	2	?	APP		UDF		INSTRUMENT APPROACH-TOUCHDOWN 5.5 MILES FROM RUNWAY
070363	CVL	CORDOBA, ARGENTINA	X	70	0	?	APP	FIRE	YES		SHORT-HIT TREES, TANKS RUPTURE, FIRE-HIT RAILROAD TRACKS-LOST GEAR
050265	720	CAIRO	X	127	121	6	APP	FIRE	UDF		HIGH RATE OF DESCENT-IMPACTED HILL IN LEFT TURN-S RVIVORS EJECTED
110865	727	CINCINNATI	X	62	58	4	APP	FIRE	PAR		IMPACTED WOODED HILL-A/C BROKE UP
030366	DC8	TOKYO	X	72	64	8	APP	FIRE	PAR		WINDSHEAR-A/C HIT APPROACH LIGHTS AND SEAWALL-SURVIVORS EJECTED
053066	TRI	KUWAIT	X	83	0	0	APP		YES		LANDED IN SANDY SOIL-SEPARATED GEAR-MINOR FUEL SPILL
122456	DC8	MEXICO CITY	X	110	0	6	APP	FIRE	YES		LANDED IN DRY LAKE BED-HIT 3FT HIGH ROAD, SHED M.G.-FUSELAGE BROKE
021566	CVL	NEW DELHI	X	81	2	14	APP	FIRE	YES		A/C HIT CEMENT PILLAR-GEAR FAILED-WING TANKS RUPTURED-FIRE
1:2067	880	CINCINNATI	X	82	70	12	APP	FIRE	PAR		IMPACTED WOODED HILL-A/C BROKE UP
030567	DC8	MONROVIA	X	90	51	23	APP	FIRE	UDF		HIGH RATE OF DESCENT-LOST ENGINES AND GEAR-HIT SEVERAL HOUSES-FIRE
060067	CVL	HONG KONG	X	80	17	5	APP		YES	WAT	SHORT, IN WATER, NOSE UP-A/C FUSELAGE BROKE-A/C SANK-PAX DROWNED
061368	707	CALCUTTA	X	63	6	2	APP	FIRE	YES		SHORT-HIT TREES AND HOUSE TOPS-LOST GEAR AND 3 ENGINES-FUEL LEAK-FIRE
021668	727	TAIPEI	X	63	21	42	APP	FIRE	UDF		SHORT-HIT TREES, FARM HOUSE, MORE TREES-A/C BROKE UP AND BURNED
C60268	DC8	MILAN	X	95	12	?	APP	FIRE	YES		WINDSHEAR-MILD IMPACT ON HILL WITH TREES-A/C INTACT-FUEL SPILL, ENGINE FIRE
010569	727	LONDON GATWICK	X	65	50	14	APP	FIRE	PAR		SHORT-HIT TREES, HOUSE A/C DISINTEGRATED IN SLIDE OUT-FIRE
011369	DC8	LOS ANGELES	X	45	15	17	APP		YES	WAT	IMPACT SANTA MONICA BAY-A/C FUSELAGE BROKE AND SANK-PAX DROWNED
092169	727	MEXICO CITY	X	118	28	78	APP		PAR	WAT	IMPACT SHORT IN SHALLOW LAKE-SLID 900 FT AND HIT 10 FT HIGH RR BED-A/C BROKE UP
091269	BAC	MANILA	X	47	45	2	APP	FIRE	PAR		HIT HILL-SURVIVORS EJECTED
072770	DC8	NAHA, OKINAWA	X	4	4	0	APP		PAR	WAT	IMPACTED WATER-A/C BROKE UP-2 CREW TRAPPED IN COCKPIT DROWNED
033170	CVL	CASABLANCA	X	82	61	21	APP	FIRE	UDF		A/C HIT POWER LINES, IMPACTED ON HIGHWAY-BOUNCED IN BALL OF FLAME-FUSELAGE BROKE
120070	BAC	CONSTANA	X	27	18	?	APP		UDF		SHORT
120872	737	CHICAGO MIDWAY	X	61	43	12	APP	FIRE	PAR		STALLED-IMPACTED HOUSES AND TREES-A/C BROKE UP-FIRE
122972	L10	MIAMI	X	176	99	?0	APP		PAR	WAT	IMPACTED IN EVERGLADES-A/C DISINTEGRATED-MOST SURVIVORS EJECTED
012172	DC9	ADANA	X	5	1	?	APP		UDF		IMPACTED ON DOWNWIND LEG AND BURNED
122372	F28	OSLO	X	45	40	?	APP		UDF		A/C IMPACTED IN FOREST-DISINTEGRATED AND BURNED
073173	DC9	BOSTON, MASS.	X	89	89	0	APP	FIRE	PAR		A/C HIT SEAWALL AND DISINTEGRATED AND BURNED
112773	DC9	CHATTANOOGA	X	77	0	0	APP	FIRE	PAR		HIT APPROACH LIGHTS-LT WING, ENGINE AND GEAR SEPARATED-FUSELAGE BROKE
053173	737	NEW DELHI	X	65	52	?	APP	FIRE	YES		SHORT-HIT BOULDERS-SEP GEAR, RT WING, #2 ENGINE-FUSELAGE BROKE AND BURNED
060973	707	RIO DE JANEIRO	X	4	2	0	APP	FIRE	YES		INADVERTENT SPOILERS-A/C HIT APPROACH LIGHTS-IMPACTED WATER
011374	707	PAGO PAGO, AM. SAMOA	X	101	97	5	APP	FIRE	YES	WAT	A/C HIT TREES, LAVA WALL, AND DITCH-TANKS RUPTURED-FIRE
091174	DC9	CHARLOTTE, N.C.	X	82	71	10	APP	FIRE	PAR		A/C LANDED IN FIELD, HIT TREES-SEPARATED GEAR AND WINGS-IMPACTED GULLEY-FIRE
010174	F28	TURIN, ITALY	X	42	38	4	APP	FIRE	UDF		IMPACT SHORT-FUSELAGE BROKE AND BURNED
062475	727	JFK	X	124	112	12	APP	FIRE	PAR		WINDSHEAR-HIT APPROACH LIGHTS-A/C BROKE UP
111275	727	RALEIGH, N.C.	X	139	0	0	APP		YES		WINDSHEAR-HARD IMPACT
111575	F28	MR. BUENOS AIRES	X	66	0	0	APP		YES		A/C HIT TREE-LOST GEAR AND LT WING TIP ON GRD IMPACT-HIT LARGE TREE
042276	720	BARRANQUILLA, COL.	X	4	0	1	APP		YES		A/C HIT TREES-LOST BOTH WINGS-FUSELAGE BROKE
030477	DC8	NIAMEY, NIGER	X	4	2	2	APP		YES		SHORT-HIT DITCHES-A/C BROKE UP IN SLIDE
040477	DC9	NEW HOPE, GA.	X	85	62	22	APP	FIRE	PAR		LANDED ON HIGHWAY-HIT TREES, POLES, CARS, BUILDINGS, FUSELAGE BROKE FIRE
092777	DC8	KUALA LUMPUR	X	79	34	?	APP	FIRE	UDF		CRASHED ON RUBBER PLANTATION
112177	BAC	BARILOCHE, ARG.	X	79	45	34	APP		UDF		IMPACTED ROCKY AREA
121877	CVL	MADEIRA	X	57	36	13	APP		YES	WAT	A/C TOUCHED DOWN IN WATER-FLOATED 5 MINUTES-PAX DROWNED
050876	727	PENSACOLA	X	58	3	11	APP		YES	WAT	IMPACTED WATER IN APPROACH-ATTITUDE-PAX DROWNED
111578	DC8	COLUMBO, SRI LANKA	X	259	195	7	APP	FIRE	UDF		CRASHED IN THUNDERSTORM-HIT COCONUT TREES-MOST SURVIVORS FROM AFT SECTION
122978	DC8	PORTLAND, OREGON	X	186	10	23	APP				RAN OUT OF FUEL-HIT POLES, BANKS, HOUSES, TREES-FWD FUSELAGE CRUSHED
021979	707	ST. LUCIA	X	170	0	0	APP		YES		HARD IMPACT-FUSELAGE FLOOR DISTORTED
031479	727	DOHA,QATAR	X	64	45	15	APP	FIRE	PAR		WINDSHEAR-HARD TAIL DOWN IMPACT-HIT BLDG

N = 46

X 64 45 15 APP FIRE PAR

HARD IMPACT-FUSELAGE-FLOOR DISTORTED ... BANK, HOUSES, TREES-FWD FUSELAGE ... SECTION CRUSHED
WINDSHEAR-HARD TAIL DOWN IMPACT-HIT BLDG

(a) Takeoff
(b) Climb
(c) Approach
(d) Landing
(e) Taxi

Table 3.3-Accidents by Operational Phase (Continued)

(d) Landing

Code / A/C / Location	Hull Loss	Onboard	Fatal	Serious Injury	Flight Phase	Fire	Impact Survivable	Water Landing	Description
022060 CMT BUENOS AIRES	X	6	0	0	LDG	FIRE	YES		HARD IMPACT-GEAR FAILED LOST POD TANKS-FIRE-TRAINING
071161 DC8 DENVER	X	122	17		LDG	FIRE	YES		HYDRAULICS FAILED-A/C VEERED OFF RUNWAY-HIT TRUCK-LOST ALL GEAR,ENG. 1,2,4-BURNED
061561 707 LISBON	X	103	0	2	LDG	FIRE	YES		HARD LDG-COLLAPSE NOSE GEAR
092761 720 BOSTON	X	71	0	2	LDG	FIRE	YES	WAT	LONG,HARD LANDING-GEAR COLLAPSE FRICTION FIRE-TANKS LEAKED
092761 CVL BRASSILA	X	7	7	1	LDG	FIRE	UDF		SHORT, HARD LANDING-GEAR COLLAPSE FRICTION FIRE TANKS LEAKED
031864 BAC WISLEY, ENG.		5	0		LDG		YES		HARD LANDING-SEPARATED ONE ENGINE, NOSE & RMG
043764 707 JFK	X	145	0	7	LDG		YES		OVERRUN-ENTERED THURSTON BASIN
032264 CMT SINGAPORE	X	36	0		LDG		YES	WAT	LMG FAILED-A/C STOPPED ON REMAINING GEAR AND LEFT WING TIP-FIRE
070165 707 KANSAS CITY	X	66	0	2	LDG	FIRE	YES		GRD LOOP ON OVERRUN-HIT BLG, LEVEE
111165 727 SALT LAKE CITY	X	91	43	35	LDG	FIRE	YES		HIGH RATE OF DESCENT-GEAR FAILURE-FUEL LINE FIRE
022765 880 IKI IS.. JAPAN	X	66	0	2	LDG	FIRE	YES		SHORT-GEAR SHEARED ON RUNWAY LIP-RUPT TANK-FIRE
092967 CMT ROME	X	4	0		LDG	FIRE	YES		HARD LDG-VEERED OFF RUNWAY-HIT CONCRETE BOX-FUEL SPILL
032868 DC8 ATLANTIC CITY	X	102	0	2	LDG	FIRE	YES		2 ENG OUT TRAINING-VEERED OFF RUNWAY HIT DITCH-LOST GEAR-ENG FIRE
020768 707 VANCOUVER, B.C.	X	61	1	4	LDG		PAR		HIT ILS TOWER-LOST GEAR
101669 DC8 STOCKTON, CA.	X	5	0		LDG	FIRE	YES		VEERED OFF RUNWAY-HIT BLG
021170 707 STOCKTON,CA	X	6	0	1	LDG	FIRE	YES		OVERRUN-HIT DITCH-LOST GEAR, ENGINE-FUEL SPILL
093870 DC9 LOUISVILLE		94	0	1	LDG	FIRE	YES		VEERED OFF RUNWAY-HIT DITCH-LOST NOSEGEAR-FRACTURED WING
122870 727 ST. THOMAS	X	55	2	11	LDG	FIRE	YES		SHORT ON 5° SLOPE-BROKE FUSELAGE-BOUNCED ONTO RUNWAY
093970 990 ACAPULCO	X	8	0	8	LDG	FIRE	YES		HARD IMPACT-BOUNCED-OVERRUN-HIT TRUCK-SLIDE UP HILL-A/C BROKE UP
050270 DC9 ST. CROIX, V.I.	X	63	25	25	LDG	FIRE	PAR	WAT	HARD IMPACT-FAILED WINGS
070570 DC8 TORONTO	X	108	108		LDG	FIRE	YES		IMPACT WATER-PAX DROWNED
041570 DC8 JFK	X	156	0		LDG	FIRE	YES		HARD-TAIL FIRST-#4 ENG HIT RUNWAY, SEPARATED-FIRE-EXPLOSION ON GO AROUND
031571 707 IRUNCHI, CHINA	X	3	0	7	LDG	FIRE	YES		HARD LDG.
051972 DC9 FT. LAUDERDALE	X	10	0	3	LDG	FIRE	YES		HARD LDG.
092472 DC8 BOMBAY	X	120	0		LNG	FIRE	YES		HARD LDG.-GEAR SEP.& TANK RUPT.
121572 747 MIAMI	X	160	0	4	LDG	FIRE	YES		RUNWAY TOO SHORT-OVERRUN HIT DITCH
122872 F28 BOLBAO, SPAIN		4	0		LDG		YES		OVERRUN-HIT CONCRETE BLG. FOUNDATION
122773 DC9 AKRON, OHIO	X	26	0	16	LDG	FIRE	YES		OVERRUN-CROSSED GULLY AND STREAM
012273 707 KHANO, NIGERIA	X	202	172	7	LDG	FIRE	YES		OVERRUN-FELL INTO 50 FT. DEEP RAVINE
102973 737 GREENSBORO		96	0		LDG		YES		SHORT-HARD-LOST RMG-LEFT WING SEPARATED-FIRE AT ROOT-FIRE DEATHS
061573 707 BUENOS AIRES		86	0	8	LDG	FIRE	YES		OVERRUN TO SMALL HILL
052373 DC8 JFK	X	128	0	3	LDG	FIRE	YES		HARD LDG.-WING HIT GRD. & SEPARATED-FIRE
021773 DC1 BOSTON	X	151	0	3	LDG	FIRE	YES		INADVERTANT SPOILER DEPLOYMENT-HARD LANDING
111073 767 NEW DELHI	X	109	0		LDG	FIRE	YES		A/C HIT APPROACH LIGHTS-LDG. & GEARS
012473 CVL MANAUS, BRAZIL	X	57	0	3	LDG		YES		A/C HIT MIDDLE MARKER BLG.
011673 707 LOS ANGELES	X	63	0		LDG		YES		OVERRUN-WENT DOWN A SLOPE TO 50 FT. BELOW RUNWAY
091174 727 PORTO ALEGRE,BRAZIL	X	74	0		LDG	FIRE	YES		HARD-NOSEDOWN IMPACT-NO FLARE
053175 737 CASPER, WYO.	X	99	0	1	LDG		YES		LONG AND FAST-WENT THROUGH 2 BRICK WALLS
032475 F28 PALEMBANG	X	62	25	1	LDG	FIRE	YES		OVERRUN-HIT ILS-DITCH
010276 DC1 ISTANBUL	X	373	0		LDG	FIRE	UDF		OVERRUN-HIT TREES
050576 727 KETCHIKAN	X	57	1	32	LDG	FIRE	YES		SHORT-LOST GEAR,ENGS.-LEFT WING SEP.
042776 727 ST. THOMAS, V.I.	X	88	37	19	LDG	FIRE	PAR		OVERRUN-FLEW OVER GULLY-LANDED IN RAVINE-WING FIRE-FUEL LEAK
022376 DC9 PHILADELPHIA	X	105	0	36	LDG	FIRE	YES		OVERRUN-WENT DOWN SLOPE, CROSSED ROAD-HIT GAS STATION-FUSELAGE BROKE-FIRE
111977 727 MADEIRA	X	164	128	36	LDG	FIRE	PAR	WAT	WHEELS UP-TAIL FIRST-SLID OFF RUNWAY
111777 747 JFK	X	3	0	0	LDG		YES		OVERRUN-SLID DOWN 75° EMBANKMENT-HIT BRIDGE-FUEL SPILL-SURVIVORS EJECTED
									VEERED OFF RUNWAY

Table 3.3-Accidents by Operational Phase (Concluded)

(d) Landing (Concluded)

	HULL LOSS	ONBOARD	FATAL	SERIOUS INJURY	FLIGHT PHASE	FIRE	IMPACT SURVIVABLE / WATER LANDING	DESCRIPTION
021178 737 CRANBROOK, B.C.	X	49	42	5	LDG	FIRE	PAR	ABORTED LDG-ATTEMPTED GO ROUND-A/C HIT LT. WING & NOSED DOWN
030378 DC8 SANTIAGO DE COMPO.	X	222	0	52	LDG		YES	OVERRUN WENT DOWN 65' EMBANKMENT
040278 737 SAO PAULO	X	42	0	0	LDG	FIRE	YES	WHEELS UP-DID NOT SHUT OFF FUEL VALVE
040478 737 CHARLROI, BELGIUM	X	3	0	0	LDG	FIRE	YES	OVERRUN-HIT ILS TOWER-TRAINING
070978 BAC ROCHESTER		77	0	1	LDG		YES	OVERRUN-HIT DITCH
122378 DC9 PALERMO, ITALY	X	129	108	?	LDG		UDF WAT	IMPACTED LEVEL-BROKE UP AND SANK-PAX DROWNED
032578 720 LONDON		82	0	?	LDG		YES	HIT YARD AND BOUNCED-NOSE GEAR COLLAPSED
042679 737 MADRAS	X	67	0	8	LDG	FIRE	YES	OVERRUN-ROUGH TERRAIN-SEP. ENG. & NG & RMLG. LMLG COLLAPSED-MINOR FIRE
100779 DC8 ATHENS	X	154	14	0	LDG	FIRE	YES	OVERRUN-CRACK IN LEFT WING-FIRE
103179 DC1 MEXICO CITY	X	87	70	17	LDG	FIRE	UDF	TOUCHDOWN-HIT VEH., SEP. MLG-AIRBORNE-HIT WING LOW-HIT BLG.

N= 57

(e) Taxi

	HULL LOSS	ONBOARD	FATAL	SERIOUS INJURY	FLIGHT PHASE	FIRE	IMPACT SURVIVABLE / WATER LANDING	DESCRIPTION
031574 CVL TEHRAN, IRAN	X	96	15	?	TAX	FIRE	YES	GEAR COLLAPSED-WING HIT GRD-FIRE
121675 747 ANCHORAGE		121	0	2	TAX		YES	SLIDE BACKWARDS OFF RUNWAY-HIT BANK
032777 747 TENERIFE	X	396	334	62	TAX	FIRE	PAR	COLLISION WITH KLM 747-WING RUPTURE-FUSELAGE CRUSHED-FIRE

N= 3

STRUCTURAL DAMAGE

The accident data base contains 133 cases involving hull loss and 20 cases involving substantial damage. There are 103 cases in which fire was present. In approximately 90% of these cases the aircraft was a hull loss.

Referring to figure 3.5, it may be seen that engine separation occurred in 55%, landing gear collapse or separation occurred in 65%, wing box breaks occurred in 45%, fuselage breaks occurred in 48%, and water ditching impact breakup occurred in 3% of the accidents. The separation of an engine and the breaking of a wing box imply fuel spills. In some instances a fuselage break in an aircraft with aft mounted engines also caused a fuel spill. Water ditching impact breakup is considered separately from fuselage breaks because in general the forces involved are different.

FIRE HAZARD

Fire was present in 103 accidents. In 95 of these cases the aircraft was a hull loss and in the others the aircraft suffered substantial damage. In addition, there were 22 accidents in which a fuel spill occurred but for which there was no fire. Some of these involved situations where the aircraft came to rest in water or where the climatic conditions, such as low temperature, precluded the vaporization of fuel or where terrain drained the fuel away from the aircraft, except for these circumstances, those cases might also involve fire casualties or further aircraft damage.

Containment of fuel, spread/scatter of fuel, and ignition of fuel constitute major areas of study for improving survivability in jet transport accidents. Ignition sources are usually present in aircraft crashes. Landing gear failure usually produces showers of sparks due to friction of structure rubbing the ground. Hot sections of engines also provide an ignition source. Electrical arcing may occur when the electrical compartment is penetrated or when electric wiring is severed as in the instance of engine/pylon separation.

CRASH ENVIRONMENT

In crashes, aircraft encounter a variety of hazards. These hazards consititute a hostile environment. In an attempt to classify this environment hazards have been divided into three general categories: terrain, water, and obstructions.

Terrain may be further separated into hazards relating to surface bearing capacity, contours and ground plane for contact by the aircraft. The characteristics of water are depth and sea state. Obstructions are divided into four groups, based roughly on the manner in which aircraft receives crash loads. These groups are columnar, impaling, frontal, and other.

The hostile environment is shown in figure 3.6. Examples of types of hazards that have been encountered in accidents in the data base are shown in parenthesis. In simple accidents, one hazard may be encountered. More complex accidents may involve several hazards encountered in various sequences.

COMMENTS ON ACCIDENT DATA

Some comments on the content of engineering data relevant to structural crashworthiness available in accident reports are in order. In general, the content of engineering data has increased over the years as the awareness of crashworthiness increased. However, data content has tended to lag behind the technology.

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                          ┌─────────────────────┐
                          │ Hostile environment │
                          └─────────────────────┘
              ┌──────────────────┼──────────────────────────┐
         ┌─────────┐                              ┌──────────────┐
         │ Terrain │                              │ Obstructions │
         └─────────┘                              └──────────────┘
      ┌──────┴──────┐                    ┌─────────────┼─────────────┐
 ┌─────────┐   ┌─────────┐          ┌──────────┐ ┌──────────┐ ┌─────────┐
 │ Contour │   │ Bearing │          │ Columnar │ │ Impaling │ │ Frontal │
 └─────────┘   └─────────┘          └──────────┘ └──────────┘ └─────────┘
```

Contour	Bearing		Columnar	Impaling	Frontal
(Hills, elevated land/gradual slope)	(Mud)		(Trees)	(Stumps)	(Building)
(Ditches)	(Sand)		(Poles)	(Posts)	(Fences)
(Embankments ±)	(Soft earth)		(Towers)		(Walls)
(Cliffs)	(Soft pavement)		(Fence posts)		(Snow banks)
(Boulders)	(Rock)				(Equipment)
(Concrete slabs)					(Other A/C)

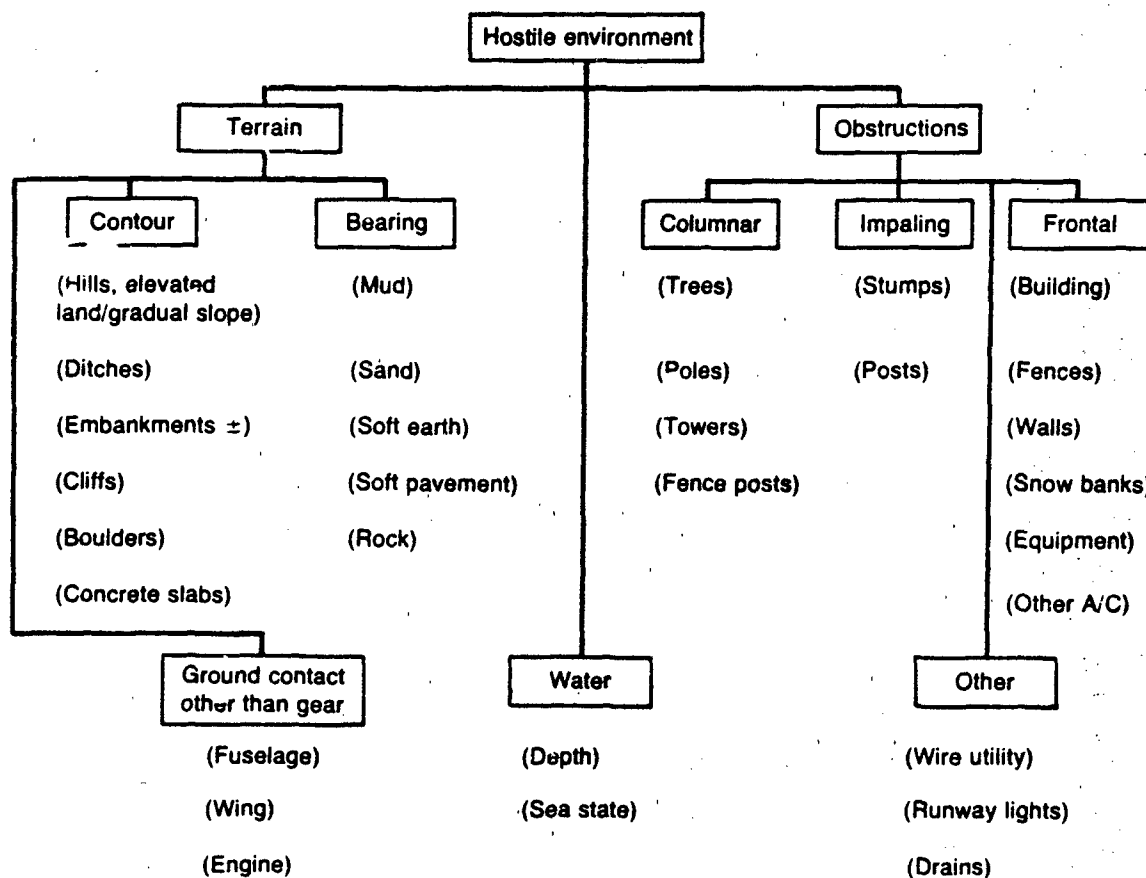| Ground contact other than gear	Water	Other
(Fuselage)	(Depth)	(Wire utility)
(Wing)	(Sea state)	(Runway lights)
(Engine)		(Drains)

Figure 3.6 – Types of Hostile Environment

NTSB reports with accident dockets contain much valuable data. Unfortunately, due to an executive order, accidents over five years old, are being deleted from their archives. Further, investigators are leaving government service through retirement, transfer, etc. making it difficult to recover data on older accidents. The NTSB should declare accidents having technical value as "classics" and preserve these dockets indefinitely.

One observation on accident reports is that it is difficult to simply differentiate accident severity between cases from the text. It is often necessary to delve through the structures and human factors reports in the dockets to make this distinction. Use of the severity index developed in the part of section 4.0 titled, Accident Severity and Survivability, of this report would help to resolve this difficulty. This index could be extended to cover fire hazard.

With due regard for the availability of data at the scene of the accident, it is felt that participation of structural subsystems reported may be influenced by the anticipations of the investigator. For instance, where fuselage breaks have occurred it may be usual for ceiling panels, sidewalls and overhead storage to be disrupted. Therefore, these items may not be mentioned in the reports. Sources and sizes of fuel spills could be better reported.

With the advent of better simulation techniques more accurate data on impact conditions, surface conditions, slide out distances, hazard definition, etc., will be useful in upgrading crashworthiness technology. Continued emphasis on the definition of injury mechanisms is needed.

Many foreign accident reports are quite thorough in the coverage of accidents while others simply report the barest details. More cooperation and assistance through ICAO or directly with the foreign agencies might upgrade these reports.

Finally, the availability of a team of crashworthy specialists drawn from NASA and the FAA to assist the investigating authorities may prove useful. The NTSB, FAA, and NASA should consider this option.

CRASH SCENARIOS

Scenarios to identify a general sequence of crash events or conditions that produce the failure mechanisms of the aircraft structure and the injury mechanisms for the aircraft occupant have been developed. Scenarios for the complete aircraft are necessary where there is significant interaction between constituent elements of the aircraft, where the sequence of damage is important to the crash response, and to establish initial conditions for the study of isolated components.

The underlying philosophy for scenario development was, first, the scenarios must produce the failure mechanisms of the structure and the injury mechanisms for the occupants. Second, the scenarios should encompass available accident experience. Third, the scenarios should assist in the identification of crash technology requirements and allow study of the crash phenomena.

SCENARIO DEVELOPMENT

The initial phase in the development of crash scenarios consisted of review and study of historical accident data to identify and define broad categories of occurrence relative to structural break-up and injury factors. Structural failure mechanisms were identified and are listed in table 3.4. Types of injuries were identified and are listed in table 3.5. The data extraction form is given in appendix B.

After an analysis of the structural and injury mechanisms, three basic scenarios evolved. These are "Air to Surface", "Surface to Surface", and "Flight Into Obstructions".

Table 3.4—Failure Mechanisms

- Fuselage

    Crush (axial & vert)
    Bending breaks
    Local deformations
    Tangential damage

- Gear

    Separation
    Collapse

- Hatch/door/floor

    Distortion
    Destruction
    Separation

- Belts/harness

    Rupture
    Ejection

- Wing

    Breaks
    Wing box destruction
    Distortion

- Engines/pylons

    Separation

- Seats

    Separation
    Distortion
    Rupture

- Interiors

    Galley/dividers separation – spillage
    Compartment separation – spillage
    Panel dislodgement

Table 3.5—Injury Types

- Trauma

    Head   Fracture, concussion
    Neck   Fracture
    Chest   Crush, rib fracture
    Spine   Fracture
    Limbs   Fracture, amputation

- Drowning

- Fire/smoke/noxious gases

    Burns
    Vascular damage
    Asphyxiation

BASIC SCENARIO — AIR TO SURFACE

This scenario considers those accidents in which the aircraft impacts a level surface from the air. The accident is characterized by high sink rates. The crash variables are shown in table 3.5.

Aircraft configuration may have individual landing gear up or down. Aircraft weight variables are the fuselage weight distribution and the fuel load distribution.

Aircraft initial conditions are three components of linear and angular velocity, and three components relating the aircraft orientation relative to the surface. Aerodynamic loads may be significant for those cases where the forward velocity is greater than V_S (stall).

Surface loads are due to the resistance of the surface. For land, this may vary from soft mud to runway hardness, while for water, loads are influenced by sea state and are in accordance with the laws of hydrodynamics. Surface load characteristics may vary as the aircraft progresses through the accident.

Following initial impact, subsequent hazards may be encountered. For simplification, obstructions are separated into three types; columns representing trees, poles, and towers that resist motion in the x and y direction and are local; the ditch or hump representing vertical terrain changes of the form Ao (1- cos XL) and may be local or apply to broad sections of the aircraft, and the step function which forms a vertical boundary representing walls, buildings, vehicles, and other obstructions.

These obstructions may be symmetrically or asymetrically located and may be applied to landing gear, engines, wings, and fuselage separately or in combination.

BASIC SCENARIO — SURFACE TO SURFACE

This scenario considers those accidents in which the aircraft on the ground encounters obstructions. The accident is characterized by horizontal motion into the hazard. As such it treats cases of hitting vehicles, buildings, soft earth, ditches or humps, entering water, and sliding contact with the surface. Accident variables are similar to those described for the Air to Surface scenario with values appropriate to the accident conditions.

BASIC SCENARIO — FLIGHT INTO OBSTRUCTION

This scenario considers those accidents in which the aircraft flies into obstructions. The accident is characterized by high kinetic energy and by the location and direction of the impact loads. Further these accidents tend to be complex, encountering a sequence of obstructions.

SCENARIO SUBSETS

The basic scenarios are divided further into subsets. The Air to Surface set has 4 subsets as follows:

S10:	no further definition	(2)
S11:	impact on other than gear	(13)
S12:	impact on gear	(31)
S13:	impact in water	(7)

Table 3.6–Crash Variables

A/C configuration

individual gear:	Up/down
Weight dist.:	Fuselage
	Fuel

A/C initial conditions: XDOT, YDOT, ZDOT $\left.\begin{array}{l}\end{array}\right\}$ Coord system
PHI, THETA, PSI aligned with inertial
PHIDOT, THEDOT, PSIDOT reference frame

Aerodynamic loads: Lift distribution

Surface loads: (Earth/water):
Spring rate (may be distributed in space)
Friction coefficient
Slope of surface

Subsequent hazards (not always encountered)

Columns

Ditch or hump   Ao (1 -cos XL)

Step function
$$\left\{\begin{array}{l} F = -Zo\,(\delta) \\ \delta = 1 \quad F = -Zo \\ \delta = 0 \quad F = 0 \end{array}\right.$$

Hazards may be   Symmetric or assymmetric

Applied to gear, engine, wing, fuselage
separately or in combination

The Surface to Surface set has 5 subsets as follows:

S20:	hard ground or on runway	(2)
S21:	soft surface	(13)
S22:	low obstruction	(35)
S23:	high obstruction	(9)
S24:	slide/roll into water	(2)

The flight into obstructions set has 4 subsets as follows:

S31:	wing low	(8)
S32:	impact column	(16)
S33:	impact solid wall	(3)
S34:	impact high obstruction	(3)

The accidents have been grouped by basic scenario and by subset in table 3.7. A fourth category (S4) contains nine accidents. For these accidents there was insufficient information in the files about the accident for scenario classification or the accident was of a peculiar nature such as the DC-8 in Shannon or the 707 in London. However, the consequences of these accidents warrant their retention in the data base.

In some instances, it was difficult to place an accident in one basic scenario rather than another. This is due in part to the complexity of some of the cases and in part to the paucity of the available accident descriptions. Effort should be made to sharpen the distinction between the existing sets and to clarify the subsets from future accidents. In addition some provision should be made for inclusion of a fuel spill factor in the subsets.

Finally, classifications have been based on history. Types of new accidents coming into the data base should have a significantly different distribution from those of the first 20 years. This distribution might be expected to be strongly affected by improvements in accident avoidance techniques and be reduction of hazards on and around airports. Development of fire suppressing fuel additives could not only alter the distribution of accidents among scenarios but could change the significance of structural component participation in accidents. If a less severe impact survivability criterion were applied to the data base, some subsets might be eliminated and the distribution of accidents by subset might be modified. Consequently, the scenarios should be reviewed at intervals to ensure their continuing applicability. Further, the scenarios should reflect current behavior rather than that drawn from the complete history.

CATEGORIZATION OF CRASH IMPACT CONDITIONS FOR CRASH SCENARIOS

An assessment of the accidents with respect to the initial conditions has been made. It should be noted that accidents in the data base are potentially impact survivable and that inherent structural capability of the airframe already provides a high level of safety. Consequently, for many accident types the areas of interest for impact research lie at the extreme limits of observed conditions or beyond. For other accidents the severity of the accidents was more a function of hazards encountered and somewhat independent of the normal initial conditions.

Crashes on approach usually occur because the aircraft is not where the pilot thinks it is. Forward speed of the aircraft is between the speed for flap deployment (V_F) and stall (V_S). The rate of descent is between 0 and 2400 ft/min. If defensive action (flare) is taken, say to avoid ground contact, even a slight climb may be achieved. However, for research purposes, the lower limit of zero may suffice. The angle of the aircraft relative to the ground is dependent on the slope of the

Table 3.7–Crash Scenarios

AIR TO SURFACE

(a) No further definition
(b) Impact on other than gear
(c) Impact on gear
(d) Impact on water

AIR TO SURFACE

Column headers (rotated): HULL LOSS · ONBOARD · FATAL · SERIOUS INJURY · FLIGHT PHASE · FIRE · IMPACT SURVIVABLE · WATER LANDING · DESCRIPTION

(a) SIZ: NO FURTHER DEFINITION

	HULL LOSS	ONBOARD	FATAL	SERIOUS INJURY	FLIGHT PHASE	FIRE	IMPACT SURVIVABLE	WATER LANDING	DESCRIPTION
011174 F28 TURIN, ITALY	X	42	38	4	AP	F	U		IMPACT SHORT-FUSE. BROKE AND BURNED
112177 DAC BARILOCHE, ARG.	X	79	45	34	AP		U		IMPACTED ROCKY AREA

(b) SII: IMPACT ON OTHER THAN GEAR

(data rows largely illegible)

description (best effort)
ENG OUT TRAINING-LOST POWER-TAIL HIT HOT-VEERED INTO ROUGH TERR
HIT CV600-IMPACTED ROT-SKIDDED 2ND R.-FIRE IN RUPT FUEL LINES
A/C STALLED-WHEELS UP-SEP BOTH ENG-FIRE LT WING
STALL-HARD IMPACT FROM 150 M. ALTITUDE
A/C FELL INTO GRD-FUSE. BROKE-6 SURVIVORS BEHIND COCKPIT
STALL DUE TO FLAP RETRACTION
NOSE HIGH STALL-AFT FUSE. HIT ELEVATED ROAD-A/C BROKE UP
IMPACTED WOODED HILL-A/C BROKE UP
HIT HILL-SURVIVORS EJECTED
NOSEHI-HARD TAIL DOWN IMPACT-HIT BLDG
HARD-TAIL FIRST-#4 ENG HIT HOT, SEP-FIRE-EXPLOSION ON GO AROUND
WHEELS UP-TAIL FIRST-SLID OFF ROT
OVERRUN-SLID DOWN U EMBANK-HIT BRIDGE-FUEL SPILL-SURVIVORS EJECT

(c) SIZ: IMPACT ON GEAR

(data rows largely illegible — descriptions best effort)

description (best effort)
ENG TRAINING-LARGE TAR & HULL-A/C HIT GRD-SLID OUT LOSING GEAR & ENG
LOST POWER-OVERRAN-CRASHED INTO 17 M DEEP RAVINE
STALL-HARD IMPACT-ENG OUT TRAINING
INGSHH-STALL
IMPACTED WOODED HILL-A/C BROKE UP
LANDED IN SANDY SOIL-SEPARATED GEAR-MINOR FUEL SPILL
HIGH RATE OF DESCENT-LOST ENGINES AND GEAR-HIT SEVERAL BLDGS-FIRE
A/C HIT POW LINES, IMPACTED ON HOT-BOUNCED IN FLAME-FUSE. BROKE
INGSHH-HARD IMPACT
HARD IMPACT-FUSE. FLOOR DISTORTED
HARD IMPACT-GEAR FAILED LOST POW TANKS-FIRE-TRAINING
HARD LUG-COLLAPSE NOSE GEAR
LONG,HARD LUG-GEAR COLLAPSE FRICTION FIRE-TANKS LEAKED
SHORT, HARD LDG-GEAR COLLAPSE FRICTION FIRE TANKS LEAKED
HARD LUG-SEP ORL ENG, NOSE & FRL
HIGH RATE OF DESCENT-GEAR FAIL-FUEL LINE FIRE.
SHORT SUBS SLOPE-HOURE FUSE.-BOUNCED ONTO ROT
HARD IMPACT-FAILED WINGS
HARD LDG.
HARD LDG.
HARD LDG.-GEAR SEP. & TANK RUPT.
OVERRUN-FELL INTO 17 M. RAVINE
SHORT-HARD-LOST PWR-LEFT WING SEP-FIRE AT ROUT-FIRE DEATHS
HARD LDG.-WING HIT GRD. & SEP-FIRE
INADVERTANT SPOILER DEPLOY-SOFT-HARD LANDING
HARD-NOSEDOWN IMPACT-NO FLAME
SHORT-LOST GEAR,ENGS.-LEFT WING SEP.
OVERRUN-FELL OVER GULLEY-LANDED IN RAVINE-WING FIRE-FULL GEAR
OVERRUN-WENT DOWN SLOPE, CROSSED ROAD-HIT GAS STA-FUSE. BROKE-FIRE
OVERRAN WENT OVER 22 M EMBANK
HIT HARD AND BOUNCED-NOSE GEAR COLLAPSED

(d) SIZ: IMPACT ON WATER

description (best effort)
SHORT, IN WATER, NOSE UP-A/C FUSE. BROKE-A/C SANK-PAX DROWNED
IMPACT SANTA MONICA BAY-A/C FUSE. BROKE AND SANK-PAX DROWNED
IMPACTED WATER-A/C BROKE UP-? CHLD TRAPPED IN CKPIT DROWNED
A/C TOUCHED DOWN IN WATER-FLOATED 5 MINUTES-PAX DROWNED
IMPACTED WATER IN APP ATTITUDE-PAX DROWNED
IMPACT WATER-PAX DROWNED
IMPACTED LEVEL-BROKE UP AND SANK-PAX DROWNED

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Table 3.7—Crash Scenarios (Continued)

SURFACE TO SURFACE

(a) Hard ground or runway
(b) Soft surface
(c) Low obstruction
(d) High obstruction
(e) Slide/roll into water

SURFACE TO SURFACE

Column headers (angled): NULL LOSS · ONBOARD · FATAL · SERIOUS INJURY · FLIGHT PHASE · FIRE · IMPACT SURVIVABLE · WATER LANDING · DESCRIPTION

(a) S2e: HARD GROUND OR RUNWAY

	NULL LOSS	ONBOARD	FATAL	SER.INJ	FLT PH	FIRE	IMP SURV	WTR	DESCRIPTION
032204 CAT SINGAPORE	X	86	0	0	LD	F	Y		LNG FAILED-A/C STOPPED ON REMAINING GEAR AND LEFT WING TIP-FIRE
031574 CVL TEHRAN, IRAN	X	96	15	7	TA	F	Y		GEAR COLLAPSED-WING HIT GND-FIRE
no 2									

(b) S21: SOFT SURFACE

072761 707 HAMBURG	X	41	0	10	TO	F	Y		VEERED -SEP GEAR, 02 & 03 ENG. BROKE FUSE-FIRE BOTH WINGS
000302 707 PARIS, ORLY	X	132	130	2	TO	F	U	OVERRUN-BRAKE FIRE-LNG SER-FIR LT WING-RNG SEP-02 LNG SEP-TWR,BLG
002002 DC8 RIO DE JANIERO	X	105	15	7	TO		Y	W	OVERRUN-LOST THRUST REVERSERS-HIT FENCE, ROAD-WATER-DROWNINGS
110007 707 CINCINNATI	X	36	1	2	TO	F	Y		ABORTED V1-OVERRUN- SEP RG-A/C DAMAGED IN SLIDE OUT-WING BREAK
071970 737 PHILADELPHIA	X	82	6	1	TO		F		LOST POWER-OVERRAN-GEAR FAILED, 01 LNG. SEP, 01 TANK RUPT
113070 707 TEL AVIV	X	3	0	0	TO	F	Y		HIT A/C UNDER TOW-LOST ENGINES AND GEAR IN SLIDE OUT
121773 DC9 GREENSBORO		91	0	0	TO		Y		LOST POWER-VEERED -LNG FOLDED-LT WING TANK RUPT
111275 DC1 JFK	X	139	0	2	TO	F	Y		ENGINE DISINT-FIRE 03 LNG-WENT OFF TAXI-WAY-RT WING LOST FUEL
041877 DC8 TOKYO	X	140	0	0	TU		Y		VEERED -LOST GEAR AND ENG
030176 DC1 LOS ANGELES	X	197	2	31	TO	F	Y		OVERRUN-LNG SEP., RUPT TANKS
091174 DC9 CHARLOTTE, N.C.	X	82	71	10	AP	F	P		A/C LANDED IN FIELD, HIT TREES-SEP. GEAR AND WINGS-HIT GULLEY-FIRE
142073 737 GREENSBORO		90	0	0	LD	F	Y		OVERRUN TO SMALL HILL
111777 747 JFK		3	0	0	LD		Y		VEERED
no 13									

(c) S22: IMPACT LOW OBSTRUCTION

112364 747 RORE	X	73	44	20	TO	F	Y		ABORTED-VEERED -HIT VEH AND LOST 04 LNG-FUEL FIRE, EXPLOSION
042000 880 TOKYO	X	5	5	0	TU	F	Y		LNG OUT TRAINING-VEERED -HIT DITCH-LOST GEAR, ENG-WING
032100 727 CHICAGO	X	3	0	1	TU	F	Y		ABORTED AT VR-OVERRAN-HIT DITCH-BROKE LT. WING, FUSE.-04 LNG. SEP.
112770 DC8 ANCHORAGE	X	229	47	07	TO	F	Y		HIT DITCH AND ANTENNA TOWER-A/C LOST PARTS-FUSE. SMOKE-FIRE
020970 CAT MUNICH	X	23	0	0	TO	F	Y		HIT FENCE-GEAR SEP.-FIRE IN MT. WING
071970 BAC GERONA, SPAIN	X	85	0	3	TU		Y		OVERRAN-HIT 6.5 M HIGH EMBANKMENT
041772 VC1 ANDES AREA	X	107	43	7	TU	F	U	LOST POWER-OVERRUN-DOWN SLOPE-HIT TWR-FIRE
020975 BAC LAKE TAHOE	X	44	0	0	TO		Y		HIT SNOW BANK-VEERED -RT WING, RNG, RG SEP
121676 80F MIAMI	X	3	0	1	TU		Y		FOU CG-OVERRUN-STOPPED IN CANAL
111676 DC9 DENVER	X	85	0	1	TU	F	Y		STALL AT VR-VEERED -HIT DITCHES AND POLES-TANK RUPT
052578 88F MIAMI	X	6	0	0	TU		Y		FWD C.G.-A/C OVERRAN AND BROKE UP
122400 DC8 MEXICO CITY	X	110	0	6	AP	F	Y		LANDED IN DRY LAKE BED-HIT 1 M HIGH ROAD, SHED R.G.-FUSE. BROKE
000200 DC8 MILAN	X	95	12	7	AP	F	Y		WINDSHEAR-MILD IMPACT HILL WITH TREES-A/C INTACT-FUEL SPILL. LNG FIRE
042107 727 MEXICO CITY	X	110	20	70	AP		P	U	IMPACT SHORT IN SHALLOW LAKE-SLID 300 M AND HIT 3 M HIGH RR BED
033173 737 NEW DELHI	X	65	52	7	AP	F	Y		SHORT-HIT BOULDERS-SEP GEAR, RT WING, 02 LNG-FUSE. SMOKE AND BURNED
030477 DC8 SIDNEY, NIGER	X	4	2	2	AP	F	Y		SHORT-HIT DITCHES-A/C BROKE UP IN SLIDE
071161 DC8 DENVER	X	122	17	0	LD	F	Y		HYDRAULICS FAILED-A/C VEERED-HIT VEH-LOST GEAR,LNG. 1,2,4-BURNED
070165 707 KANSAS CITY	X	66	0	2	LD		Y		GND LOOP ON OVERRUN-HIT BLG, LEVEL
022765 88F IKI Is., JAPAN	X	0	0	2	LD	F	Y		SHORT-GEAR SHEARED ON ROT LIP-RUPT TANK-FIRE
092967 CAT RORE	X	66	0	0	LD		Y		HARD LDG-VEERED OFF RWY-HIT CONCRETE BOX-FUEL SPILL
032080 DC8 ATLANTIC CITY	X	4	0	2	LD	F	Y		2 LNG OUT TRAINING-VEERED HIT DITCH-LOST GEAR-LNG FIRE
141069 DC8 STOCKTON, CA.	X	5	0	0	LD	F	Y		OVERRUN-HIT DITCH-LOST GEAR, LNG-FUEL SPILL
021170 707 STOCKTON,CA	X	6	0	1	LD		Y		VEERED -HIT DITCH-LOST NOSEGEAR-FRACTURED WING
120670 727 ST. THOMAS	X	55	2	11	LD	F	Y		HARD IMPACT-BOUNCED-OVERRUN-HIT VEH-SLIDE UP HILL-A/C BROKE UP
092073 DC8 MOMBAY	X	100	0	0	LD	F	Y		ROT TWO SHORT-OVERRUN HIT DITCH
121572 747 MIAMI	X	100	0	0	LD		Y		OVERRUN-HIT CONCRETE BLG. FOUNDATION
122072 928 BULRAU, SPAIN	X	4	0	0	LD		Y		OVERRUN-CROSSED GULLEY AND STREAM
122073 CVL MANAUS, BRAZIL	X	57	0	1	LD		Y		OVERRUN-WENT DOWN A SLOPE TO 17 M. BELOW RWY
041174 727 PORTO ALEGRE,BRAZIL		74	0	0	LD		Y		LONG AND FAST-WENT THROUGH 2 BRICK WALLS
070970 BAC BUCHAREST		77	0	1	LD		Y		OVERRUN-HIT DITCH
042079 737 PALMAS	X	87	0	0	LD	F	Y		OVERRUN-ROUGH TERR-SEP. LNG. & RG & HALL. LMLG COLLAPSED-MINOR FIRE
100779 DC8 ATHENS	X	154	14	0	LD	F	Y		OVERRUN-CRACK IN LEFT WING-FIRE
103179 DC1 MEXICO CITY	X	87	70	17	LD	F	U	TOUCHDOWN-HIT VEH,SEP RLG-AIRBORNE-HIT WING LOW-HIT BLG
121675 747 ANCHORAGE		131	0	2	TA		Y		SLIDE BACKWARDS OFF RWY-HIT BANK
032777 747 TENERIFE	X	396	334	62	TA	F	P	COLLISION WITH RLR 747-WING RUPT-FUSE. CRUSHED-FIRE
no 35									

(d) S23: IMPACT HIGH OBSTRUCTION

011901 DC8 JFK	X	100	0	7	TO	F	P	ABORTED V1-OVERRUN-HIT FENCE-CROSSED BLVD-KILLED FLT DECK CREW
020700 707 VANCOUVER, B.C.	X	81	1	0	LD		P	VEERED -HIT BLG
122700 DC9 SIOUX CITY	X	66	0	3	TO		Y	ABORTED AT V1-SLIDE OFF ROT INTO TREES
010500 727 LONDON GATWICK	X	65	50	14	AP	F	P	SHORT-HIT TREES, BLG A/C DISINT. IN SLIDE OUT-FIRE
011409 BAC MILAN	X	33	0	0	TO		Y	LOST POWER AT VR-WHEELS UP LDG.-SLID INTO TREES
001372 707 JFK		106	0	0	TO	F	Y	OVERRAN-HIT BLAST FENCE-BROKE LEFT WING-FIRE
033175 737 CASPER, WYO.	X	99	0	1	LD		Y	OVERRUN-HIT ILS-DITCH
092473 928 PALERMO	X	82	25	7	LD	F	U	OVERRUN-HIT TREES
000470 737 CHARLEROI, BELGIUM	X	3	0	0	LD	F	Y	OVERRUN-HIT ILS TOWER-TRAINING
no 9									

(e) S24: SLIDE/ROLL INTO WATER

000704 707 JFK	X	145	0	7	LD		Y	W	OVERRUN-ENTERED THURSTON BASIN
110507 880 HONG KONG	X	127	1	7	TO		Y	W	ABORT-VEERED INTO BAY-FUSE. BROKE & SANK-DROWNING
no 2									

Table 3.7-Crash Scenarios (Concluded)

FLIGHT INTO OBSTRUCTION
(a) Wing low
(b) Impact column
(c) Impact solid wall
(d) Impact high obstruction

FLIGHT INTO OBSTRUCTION

Column headers (angled): NULL LOSS, ONBOARD, FATAL, SERIOUS INJURY, FLIGHT PHASE, FIRE, IMPACT SURVIVABLE, WATER LANDING, DESCRIPTION

(a) 531: ENG LOS
	NULL LOSS	ONBOARD	FATAL	SERIOUS INJURY	FLIGHT PHASE	FIRE	IMPACT SURV	DESCRIPTION
076466 DC8 AUCKLAND	X	5	2	1	TO	F	P	ENGINE OUT TRAINING-MT. WING HIT GRD-A/C BROKE UP
030573 707 DENVER		3	0	0	TO	F	I	3 ENG FERRY FLT-LT WING HIT GND-A/C VEERED
062469 880 MOSES LAKE	X	5	3	7	CL	F	T	ENGINE OUT-TRAINING-A/C HIT ON RT. WING-SLID 1000 M.-FIRE
010274 F28 IZMIR, TURKEY	X	72	63	7	CL	F	U	AT 10 M. BANKED LEFT AND CRASHED-PROBABLY STALL
024979 DC9 PARI	X	5	0	1	CL		I	ENG OUT TRAINING-WING HIT GRD
122972 L10 MIAMI	X	176	99	60	AP	F	P	IMPACTED IN EVERGLADES-A/C DISINT.-MOST SURVIVORS EJECTED
050265 720 CAIRO	X	127	121	6	AP		U	HIGH RATE OF DESCENT-IMPACTED HILL IN LEFT TURN-SURVIVORS EJECTED
021178 737 CRANBROOK, B.C.	X	49	42	5	LD	F	P	ABORTED LDG-ATTEMPTED GO ROUND-A/C HIT LT. WING & NOSED DOWN

(b) 532: IMPACT COLUMN
	NULL LOSS	ONBOARD	FATAL	SERIOUS INJURY	FLIGHT PHASE	FIRE	IMPACT SURV	DESCRIPTION
010576 VV0 STOCKHOLM	X	10	5	4	CL		P	3 ENG FERRY FLT-IMPACT TREES,GND WITH WING-FUSE. AFT OF CKPIT DEST
060477 LC9 NEW HOPE, GA.	X	85	62	22	AP	F	P	LANDED ON HWY-HIT TREES, POLES, CARS, BUILDINGS, FUSE. BROKE FIRE
101959 707 USO, WASHINGTON	X	0	4	0	AP	F	P	ATTEMPTED CRASH LDG IN RIVER-HIT TREES-FOO FUSE. DESTROYED
070303 CVL CORDOBA, ARGENTINA	X	70	0	7	AP	F	T	SHORT-HIT TREES, TANKS RUPT, FIRE-HIT RR TRACKS-LOST GEAR
0215AM CVL NEW DELHI	X	01	2	14	AP	F	U	A/C HIT CEMENT PILLAR-GEAR FAILED-WING TANKS RUPT.-FIRE
001308 707 CALCUTTA	X	03	0	2	AP	F	T	SHORT-HIT TREES BLG TOPS-LOST GEAR AND 3 ENG-FUEL LEAK-FIRE
071008 727 TAIPEI	X	63	21	42	AP	F	U	SHORT-HIT TREES, BLG, MORE TREES-A/C BROKE UP AND BURNED
122572 626 OSLO	X	45	40	7	AP	F	U	A/C IMPACTED IN FOREST-DISINT. AND BURNED
112774 DC9 CHATTANOOGA	X	77	0	5	AP	F	I	HIT APP LIGHTS-LT WING, ENG AND GEAR SEPARATED-FUSE. BROKE
060973 707 RIO DE JANEIRO		0	2	0	AP		P	INADVERTENT SPOILERS-A/C HIT APP LIGHTS-IMPACTED WATER
011174 747 PAGO PAGO.	X	101	97	5	AP	F	T	A/C HIT TREES, LAVA WALL, AND DITCH-TANKS RUPT.-FIRE
131575 120 MK. MOLMOS AIRES	X	00	0	0	AP	F	T	A/C HIT TREE-LOST GEAR AND LT WING TIP ON GND IMPACT-HIT LARGE TREE
042276 720 BARRANQUILLA, COL.	X	0	0	1	AP	F	T	A/C HIT TREES-LOST BOTH WINGS-FUSE. BROKE
122578 DC8 PORTLAND, OREGON	X	100	10	23	AP		P	OUT OF FUEL-HIT POLES, BANKS, BLGS, TREES-FOO FUSE. CRUSHED
001308 727 JFK		102	0	4	LD		I	HIT ILS TWR-LOST GEAR
121773 DC1 BOSTON	A	151	0	3	LD	F	T	SA/C HIT APP LIGHTS-ENG. & GEARS SEP

(c) 533: HIT SOLID WALL
	NULL LOSS	ONBOARD	FATAL	SERIOUS INJURY	FLIGHT PHASE	FIRE	IMPACT SURV	DESCRIPTION
030466 DC8 TOKYO	X	72	64	0	AP	F	U	WINDSHR-A/C HIT APP LIGHTS AND SEAWALL-SURVIVORS EJECTED
073173 DC9 BOSTON, MASS.	X	89	89	6	AP	F	P	A/C HIT SEAWALL AND DISINT. AND BURNED
062675 727 JFK	X	124	112	12	AP	F	P	WINDSHR-HIT APP LIGHTS-A/C BROKE UP

(d) 534: HIT HIGH OBSTRUCTION
	NULL LOSS	ONBOARD	FATAL	SERIOUS INJURY	FLIGHT PHASE	FIRE	IMPACT SURV	DESCRIPTION
032777 747 TENERIFE	X	246	246	0	TO	F	P	A/C HIT PAA 747-LOST LEG AND 02 ENG.-HIT RWY AND BURNED
120672 737 CHICAGO MIDWAY	A	61	43	12	AP	F	P	STALLED-IMPACTED BLGS AND TREES-A/C BROKE UP-FIRE
121973 707 NEW DELHI	X	109	0	3	LD	F	I	A/C HIT MIDDLE MARKER BLG.

INSUFFICIENT DATA FOR CLASSIFICATION

54: UNCLASSIFIED
	NULL LOSS	ONBOARD	FATAL	SERIOUS INJURY	FLIGHT PHASE	FIRE	IMPACT SURV	DESCRIPTION
100277 DC8 SHANNON	X	250	0	1	TO	F	T	WHEEL FAILURE-HIT MAIN TANK PUNCTURE-FUEL FED FIRE
040866 707 LONDON	X	127	5	7	CL	F	T	02 ENG DISINT-LOST 02,-FAILED TO SHUT OFF FUEL VALVE-FIRE DEATHS
090671 BAC HAMBURG	X	121	22	7	CL	F	U	LOST ALL POWER AT 50 M-CRASHED ON AUTOBAHN-HIT BRIDGE
062759 CRT ASCUNCION	X	56	2	7	AP		U	INSTRUMENT APPROACH-TOUCHDOWN 9 KM FROM RWY
120370 BAC CONSTANA	X	27	10	7	AP		U	SHORT
012172 DC9 ADANA	X	5	1	I	AP	F	T	IMPACTED ON BOUNDING LEG AND BURNED
092777 DC8 KUALA LUMPUR	X	79	34	7	AP	F	U	CRASHED ON RUBBER PLANTATION
111578 DC8 COLUMBO, SRI LANKA	X	250	199	7	AP	F	U	THUNDERSTORM-HIT COCONUT TREES-MOST SURVIVORS FROM AFT SECT
040278 737 SAO PAULO	X	42	0	0	LD	F	T	WHEELS UP-DID NOT SHUT OFF FUEL VALVE

ground and the attitude of the aircraft. An aircraft attitude of -5° was observed in the 727 Cincinnati accident where a 9° ground slope was encountered. The upper limit is the angle at stall speed as in the 737 accident at the Chicago-Midway airport. The aircraft gross weight is, weight at takeoff less weight of fuel burned.

For landing accidents, forward speed may be above the prescribed landing speed or at stall speed. Instances of higher speeds generally resulted in overruns. Forward speed at onset of overrun is usually less than the prescribed landing speed due to pilot deceleration measures. Angle of incidence is between 2.5° nose down to the nose up stall angle. Rate of descent is between 0 and 2400 ft/min.

The forward speed in taxi accidents is less than 60 kts. Takeoff accidents involve forward speeds of up to rotation speed (V_R) for both overrun, veer-off of runway, and contact with obstructions on the runway. Aircraft gross weight ranges up to maximum takeoff gross weight. Aircraft attitude is essentially wings level and zero incidence.

Accidents for initial climb involve loss or reduction in power and/or wing stall. Forward speed range is from V_R to V_F. These accidents may involve impacts where the aircraft is tail-down or wing low, or large angles of yaw and roll or a combination of the above. Rate of descent might be expected to be in the range of that for a hard landing, i.e., 0 to 2400 ft/min.

It should be noted that the accident data reports do not contain sufficient identification of conditions at the onset of the crash to be more precise. Techniques are being developed by NASA Ames that could better define these initial conditions where data from the Flight Data Recorder and from the Air Traffic Controller radar is used. However, to date no program to establish these values exists.

Further, effects of last second evasive actions by the flight crew and influence of terrain features on "effective" impact conditions must be included for purposes of simulating the crash. Flight crew actions may be obtained from further development of the Ames technology.

Value limits of initial conditions observed for each subset scenario are shown in table 3.8. These values may be used to give approximate ranges of crash initial conditions for the scenarios for research.

Table 3.8-Value Limits of Initial Conditions

	Fwd. Vel. (KIAS)		Normal Vel. (Ips)		Roll (DEG)		Pitch (DEG)		Yaw (DEG)		Notes
	Lwr.	Upper	Lwr.	Upper	Lwr.	Upper	Lwr.	Upper	Lwr.	Upper	
Air to Surface											
S11: Impact Other than Gear	VS	180[1]	DS	70[2]	0	-	-5	15	-	-	
S12: Impact on Gear	46[3]	VF		60[3]	0	-	-16[3]	15	-	-	
S13: Impact in Water	VS	VF	DS	33	0	-	0	15	-	-	
Surface to Surface											
S20: Hard Grd.	10	VS		23[4]	0	-			0	-	
S21: Soft Surface	60	170[5]	0	-	0	-	0	-	0	-	
S22: Low Obstruction	-10[6]	VR	0	-	0	-	0	-	0	+45[7]	
S23: High Obstruction	-	V1	-	-	0	-	0	-	0	-	
S24: Slide into Water	40	80[8]	0	DS	0	-	0	15	0	15	
Flt. into Obstruct.											
S31: Wing Low	VS	215[9]	-	33	0	80[10]	-30[10]	15	0	40[11]	
S32: Impact Column	VS	VF	-	33	-	-	0	15	-	-	
S33: Solid Wall	VS	VF	-	100[12]	-	-	0	15	-	-	
S34: High Obstruction	VS	VF	-	33	-	-	0	15	-	-	

Notes:

VS = Stall Speed
DS = Design Sink Speed
VF = Flap Speed
VR = Rotation Speed
V1 = Decision Speed
1) 880 Cincinnati
2) 727 Doha
3) DC9 Toronto
4) CVL Singapore wing tip
5) 707 Orly
6) 747 Anchorage
7) 727 St. Thomas
7) 707 Kansas City
8) 880 Hong Kong
9) L1011 Miami
10) 737 Cranbrook
11) 880 Moses Lake
12) DC-9 Boston effective normal vel. to seawall

4.0 ROLE OF STRUCTURAL COMPONENTS IN CRASHWORTHINESS

In this section the structural components that significantly participate in or influence the crash dynamic behavior are studied. Aircraft structural components that participate and their role in crashes are identified from the accident data. This participation is summarized.

A matrix relating the participation of structural systems to the scenarios defined in section 3 is presented and assessed. An accident structural damage severity index is presented. This index is a function of major component participation. The relationship between the scenario and the structural damage severity index is assessed.

Interactions of the structural components as observed from the accident data have been identified and discussed. Problem areas for current structural components are discussed and assessed. Finally, crashworthiness implications of the application of advanced materials in these structural components are considered.

PARTICIPATION OF STRUCTURAL COMPONENTS

IDENTIFICATION OF STRUCTURAL COMPONENTS

The accident data base was reviewed to identify structural components that participate in the aircraft crash dynamic response. Results of this review are shown in table 4.1. This table identifies the component crash function, crash dynamics, interaction with other components, and results of this interaction.

The components are the landing gear, pylon/engine, wing box structure, fuselage, fuel distribution system, floor structure, seats/restraint systems, cabin interior, and entry and escape doors. The landing gear includes nose gear, wing mounted main landing gear, and wide-body fuselage mounted gear. Pylon/engine include wing pod mounted engines and aft body engines. Wing box structure is concerned basically with fuel tankage and primary load carrying members. Fuselage includes lower fuselage, (bottom of fuselage to the cabin floor structure) and upper fuselage (floor structure to crown). Cabin interiors include overhead storage, galleys, closets, dividers, lavatories, ceiling panels, sidewalls, etc.

COMPONENT PARTICIPATION

Participation is summarized in table 4.2. The major diagonal gives the total participation of any component while the off-diagonal values shows coparticipation of other components. In addition to the components, hull losses and accidents involving fire are included.

From these data, general component participation and interaction of components may be obtained. However, in order to obtain the significance of the interaction and role of components in crashes a more detailed assessment is required (see part of section 4.0 titled, Interaction of Structural Components).

MATRIX CATEGORIZATION

Table 4.3 presents a matrix relating critical structural components, fatalities, and accident severity to the crash scenarios. Fatalities are divided into groups by cause: fire related, trauma, drowning, and unknown (UNK). Percentiles relate to the number of occupants participating. The known frequency of participation of structural components identified is shown for each major scenario and for subsets. Included in this table are the number of accidents, hull losses, and fires. Finally, the frequency of occurrence for each accident severity defined in table 4.3 is shown.

Table 4.1–Structural Systems

System	Crash Function	Crash Dynamics	Interaction	Direct Result
Landing Gear	• Energy Absorption • Maintain Grd. Clearance • Separate with no Damage to Airframe	• Stroke/Gear Deformation	• Load Airframe	• Energy Absorption by Gear
Nose		• Collapse Aft/Side &/or Sep.	• Forward Fuselage Grd. Contact • Penetrate Lower Fuselage	• Energy Absorption by Grd. Friction • Energy Absorption by Lwr. Fuse. Def. • Gear Damage • Floor Deformation • Fire Entry to Cabin • Fuselage C-eak
Main/Body		• Collapse or Separation Aft/Side	• Center Fuselage • Lwr. Fuse. Penetration • Wing Pod Grd. Contact • Wing Grd. Impact • Wing Box Tear • Slewing of A/C • Lwr. Fuse. Penetration • Aft Structure Contact	• Water/Fuel/Fire Entry to Lwr. Fuse. • Energy absorption by Pylon Def. • Grd. impact loads to Wing • Fuel Spill/Fire • Fuselage Break • Body Fuel Line Break/Fire • Empennage Damage
Wing Pylon/Engine	• React Obstructions • Energy Absorption • Separate with no Damage to Airframe • Provide Grd. Reaction	• Deformation • Collapse/Separation	• Load Wing Structure • Fuel/Electric/Hydraulic Line Rupt. • Wing Box Web Tear • Wing Lower Surface Penetration • Wing Ground Contact	• Pylon/Engine Damage • Energy Absorption • Load Wing Structure • Grd. Friction • Pylon/Engine Damage • Fluid Spill/Arcing/fire • Wing Box Break • Energy Absorption

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Table 4.1–Structural Systems (Continued)

System	Crash Function	Crash Dynamics	Interaction	Direct Result
Aft Pylon/Engine	. Separate with no Damage to Airframe	. Deformation/Separation	. Fuel/Electric Line Rupture	. Pylon/Engine Damage . Fuel Spill/Arcing/Fire . Fuselage Fire damage
Wing Structure	. Support Main Gear . Support Engine/Pylon	. Deformation	. Load Fuse. Structure	. Energy Absorption . Fuel Leak . Wing Damage
	. Contain Fuel . Reacts Obstructions	. Separation	. A/C Dynamics/ Flotation Loss . Hinder Egress	. Fuel Spill/Fire . Wing Damage
	. Prevent A/C Roll . Energy Absorption	. Wing Box Break	. A/C Dynamics/ Flotation Loss	. Fuel Spill/Fire . Wing Damage
	. Egress Route . Provide Flotation	. Lower Surface Tear	. Fuel Spill/Fire . Wing Damage	
Fuselage	. React Obstructions	. Lower Fuselage Crush	. Floor Displacement	. Energy Absorption by Deformation . Energy Absorption by Grd. Friction . Fuel/Fire/Smoke/ Water/Mud Entry . Flotation Loss
			. Cargo Displacement	. Fuselage Damage . Fuel Spill/Arcing . Floor Elevation
	. Protective Shell		. Upper Fuselage Distortion . Body Fuel/Elec. Line Rupture	. Survivable Vol. Loss
	. Energy Absorption	. Upper Fuselage Distortion	. Seats . Door/Hatches . Cabin Interior . Floor Structure	. Survivable Vol. Loss . Egress Blockage . Seat Lateral Displace.
	. Flotation . Egress	. Fuselage Break	. Seats/Track/Floor Beam	. Energy Absorption by Deformation . Survivable Vol. Loss . Occupant Ejection/ Egress Route . Loose Cabin Interior Items
			. Cabin Interior Items . Doors/Hatches	
			. Body Fuel Lines	. Floor/Seat Track Rupture . High Floor Accel.

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Table 4.1-Structural Systems (Concluded)

System	Crash Function	Crash Dynamics	Interaction	Direct Result
	• Support Floor Beams • Support Cabin Interior Items	• Fuselage Disintegration	• Floor Struc. Displace. • Seats • Cabin Interior Items	• Fuel/Fire Entry • Seat Separation/Ejection • Cabin Debris • Flotation Loss • Energy Absorption • Fuselage Damage
	• Constrain/Baggage-Cargo			
Fuel Tank Storage System	• Retain Structural Integrity • Limit Fuel Spillage	• Engine Line Rupture • Body Line Rupture	• Pylon/Engine • Fuselage	• Fuel Spill
Floor Structure	• Restrain Seats/Tracks • Energy Absorption • Provide Egress • Cabin Interior Items • Retain Structural Integrity	• Deformation • Rupture	• Seat Track/Seats • Cabin Interior Items • Doors/Hatches • Seat Tracks/Seats • Cabin Interior Items	• Energy Absorption • Egress Blockage
Seats/Restraints System	• Occupant Containment/Protection • Energy Absorption • Remain Attached to Floor • Release as Required (Belts/Harness)	• Seat Track Deform./Rupt. • Seat Deformation • Seat Rupture • Belt/Harness Rupture	• Floor Beams • Seat Tracks • Seats Structure • Bulkhead Structure	• Seat Elevation/Separat. • Energy Absorption • Load Limiting • Occupant Release/Injury • Occupant Ejection/Injury • Energy Absorption
Cabin Interior Svs.	• Contents Containment • Remain Attached to Structure	• Overhead Compart. Spillage • Overhead Compart. Sep. • Ceiling Panel/Sidewall Sep. • Galley/Closet/Divider Sep. • Galley/Closet Spillage	• Upper Fuselage • Floor Beams	• Cabin Debris • Egress Blockage • Occupant Injury
Entry and Escape Doors	• Operate As Required	• Blockage by Debris • Jammed by Floor • Jammed by Fuselage Distort. • Inadvertent Opening	• Cabin Interior Systems • Floor Structure • Upper Fuselage	• Egress Blockage • Fuel/Fire/Smoke Entry

Table 4.2—Component Participation

Numbers of Accidents - 153 Total

	Hull Loss	Fire	Gear Sep.	Engine Sep.	Fuselage Crush & Break	Tank Rupture	Cabin Interior	Seats	Doors	Floors	Body Fuel Lines	Water
Hull	133	95	80	70	90	100	37	36	40	32	7	15
Fire	95	103	64	59	70	85	25	27	28	21	5	4
Gear	80	64	95	57	62	71	33	26	38	33	5	8
Engine	70	59	57	80	61	61	30	28	28	26	4	10
Fuselage	90	70	62	61	100	73	34	38	41	38	5	14
Tank	100	85	71	61	73	107	33	32	31	25	6	10
Cabin	37	25	33	30	34	33	45	26	24	22	2	7
Seats	36	27	26	28	38	32	26	41	23	24	3	5
Doors	40	28	38	23	41	31	24	23	47	30	3	5
Floors	32	21	33	26	38	25	22	24	30	42	3	7
Lines	7	5	5	4	5	6	2	3	3	3	7	2
Water	15	4	8	10	14	10	7	5	5	7	2	16

Table 4.3–Categorization by Scenario

SCENARIO	OCCUPANTS	FATALITIES	% OCCUPANTS	FIRE FATALITIES	% OCCUPANTS	TRAUMA	% OCCUPANTS	DROWN	% OCCUPANTS	UNKNOWN	% OCCUPANTS	NUMBER OF ACCIDENTS	HULL LOSS	FIRE	FUSELAGE	TANK RUPTURE	ENGINE SEPARATION	CABIN INTEGRITY	SEATS	GEAR SEPARATION	DOORS	FLOORS	LINES	WATER	SEV 1	SEV 2	SEV 3	SEV 4	SEV 5	SEV 6	SEV UNK
S1: AIR TO SURFACE	4447	1391	31.3	452	10.2	133	3.0	202	4.5	604	13.6	53	44	33	40	35	25	17	18	32	21	18	4	9	2	7	14	10	11	8	1
S10: no further definition	121	83	68.6	0	0	45	37.2	0	0	38	31.4	2	2	1	1	1	3	0	0	0	0	0	0	0	0	0	0	0	0	1	1
S11: impact on other than gear	1141	677	59.3	150	13.1	76	6.7	0	0	451	39.5	13	13	12	11	12	9	1	6	5	3	1	1	1	0	1	3	0	3	6	0
S12: impact on gear	2749	425	15.5	302	11.0	8	.3	0	0	115	4.2	31	22	20	23	18	14	12	10	23	14	12	2	1	2	6	10	7	5	1	0
S13: impact in water	436	206	47.2	0	0	4	.9	202	46.3	0	0	7	7	0	5	4	2	4	2	4	4	5	1	7	0	0	1	3	2	1	0
S2: SURFACE TO SURFACE	4974	989	19.9	412	8.3	214	4.3	16	.3	347	7	61	52	39	34	39	33	21	13	45	15	13	3	4	1	14	17	10	13	4	2
S20: hard ground or on runway	182	15	8.2	15	8.2	0	0	0	0	0	0	2	2	2	0	2	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0
S21: soft surface	1127	219	19.4	37	3.3	41	3.6	15	1.3	126	11.2	13	10	10	7	10	9	7	2	13	3	2	0	1	0	4	4	1	2	2	0
S22: low obstruction	2702	676	25.0	315	11.7	165	6.1	0	0	196	7.3	35	30	22	19	21	16	10	8	26	9	9	2	1	1	7	7	7	10	1	2
S23: high obstruction	681	78	11.5	45	6.6	8	1.2	0	0	25	3.7	9	8	5	6	6	6	2	2	4	2	2	1	0	0	3	4	0	1	1	0
S24: slide/roll into water	282	1	.4	0	0	0	0	1	.4	0	0	2	2	0	2	0	2	2	1	0	1	0	0	2	0	0	0	2	0	0	0
S3: FLIGHT INTO OBSTRUCTIONS	2278	1134	49.8	462	20.3	100	4.4	0	0	572	25.1	30	28	24	23	28	19	7	10	18	11	11	0	3	0	2	9	2	9	7	1
S31: wing low	442	332	75.1	32	7.2	18	4.1	0	0	282	63.8	8	7	7	7	7	5	1	2	3	3	3	0	1	0	1	1	0	3	3	0
S32: impact-column	1135	249	21.9	125	11.0	63	5.6	0	0	61	5.4	16	15	11	11	15	9	5	5	11	6	6	0	2	0	1	6	2	5	2	0
S33: impact solid wall	285	264	92.6	35	12.3	0	0	0	0	229	80.4	3	3	3	3	3	2	0	2	1	0	1	0	0	0	0	0	0	0	2	1
S34: impact high obstruction	416	289	69.5	270	64.9	19	4.6	0	0	0	0	3	3	3	2	3	3	1	1	3	2	1	0	0	0	0	2	0	1	0	0
S4: UNCLASSIFIED	969	277	28.6	30	3.1	29	3.0	0	0	216	22.5	9	9	7	3	5	3	0	0	0	0	0	0	0	2	1	0	0	2	1	3
GRAND TOTAL	12668	3791	29.9	1356	10.7	476	3.3	218	1.7	1741	13.7	153	133	103	100	107	80	45	41	95	47	42	7	16	5	24	40	22	35	20	7

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On the basis of percent of fatalities, flight into obstructions (S3) is the most lethal scenario, followed by air to surface (S1), unclassified (S4), and surface to surface (S2). This order tends to agree with the total energy to be dissipated in the crash. The frequency of fire, while not independent of the total energy, further increases the lethality of the scenario. In fact, the major factor in fatalities is fire.

Considering total fatalities, the ranking of the basic scenarios is air to surface (S1), flight into obstructions (S3), surface to surface (S2), and unclassified (S4). On the basis of numbers of accidents, the ranking becomes surface to surface (S2), air to surface (S1), flight into obstructions (S3), and unclassified (S4).

No single scenario appears to be "the major type for lethality", rather each must be studied to fully understand the crash response of aircraft. As starting points, it appears that air to surface-impact on gear (S12), surface to surface—low obstruction (S22), and flight into obstruction—impact column (S32) are likely candidates.

To obtain improved crashworthiness each structural component must perform its crash function. For instance, when the strength capability of landing gear is exceeded, the gear should separate without tearing fuel tanks or damaging fuel or hydraulic lines. Landing gear should perform in each scenario over the range of accident variables. In like manner each system should be studied. This should provide an envelope of capabilities for the aircraft.

ACCIDENT SEVERITY AND SURVIVABILITY

Accidents have been assessed on the basis of amount of damage to the aircraft and effect of this damage on survivability. Accidents in the data base were assessed into six categories of accident severity shown in table 4.4. In general, the degree of structural damage and the energy to be dissipated increases as the category increases.

Categories 1 through 3 involve accidents in which the occupant protective shell is generally maintained but fuel spill factor increases with category. At category 4, the fuselage break is introduced but the fuel system is intact. Three classes of fuselage break are used to distinguish the severity of the accident. A class 1 break has the fuselage broken with fuselage sections essentially remaining together. The opening allows fuel/fire entry but is too small for occupant egress. In class 2 breaks, the fuselage separates sufficiently to allow occupant egress and fuel/fire entry, but the section maintain a proximity to one another. Class 3 breaks have fuselage sections separate and come to rest at some distance from each other.

Category 4 accidents are severe accidents involving either severe lower fuselage crush or class 1 or 2 breaks, or both. However, in category 4 there are no major fuel spills. Categories 5 and 6 involve increasingly severe destruction of the aircraft with serious breaks in fuel tankage.

The 151 accidents in the data base have been grouped by category and are summarized in table 4.5 and figure 4.1. From data in table 4.5 and figure 4.1 some general observations may be made. First, with regard to overall survivability, fire presents the greatest hazard. Known fire fatalities outnumber known trauma fatalities by 2.84 to 1.0. Fire hazard is most severe for accidents having major fuel spills due to rupturing of fuel tankage (categories 3, 5, and 6).

Trauma fatalities occur mostly in categories 5 and 6 which involve severe fuselage breaks. The single instance in category 2 resulted from a local loss of survivable volume and five instances in category 3 resulted from severe lower fuselage crush.

Deep water impact accidents represent less than 10% of the study data base but have a high fatality

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Table 4.4-Categories of Accident Severity

1. Minor impact damage – includes engine/pylon damage or separation, minor lower fuselage damage, and minor fuel spillage.

2. Moderate impact damage – includes higher degrees of damage of category 1 and includes gear separation or collapse.

3. Severe impact damage but no fuselage break – includes major fuel spillage due to wing lower surface tear and wing box damage.

4. Severe impact damage – includes severe lower fuselage crush and/or class 1 or class 2 fuselage breaks, may have gear collapse, but no tank rupture.

5. Extreme impact damage – includes class 1 or class 2 fuselage breaks with wing separation or breaks, may have gear and/or engine separation, and fuel spillage.

6. Aircraft destruction – includes class 3 fuselage breaks or destruction with tank rupture, gear and/or engine separation.

Fuselage breaks: Class 1 – sections break but remain together

                    Class 2 – sections break and open

                    Class 3 – sections break and move off

Table 4.5—Summary of Fatalities

Cat	Accidents	Hull Loss	Fire	Occupants	Total Fat. #	Total Fat. %	Fire #	Fire %	Trauma #	Trauma %	Drowning #	Drowning %	Unk. #	Unk. %
1	5	3	4	616	53	8.6	53	8.6	0	0	0	0	0	0
2	24	12	6	1684	1	.06	0	0	1	.06	0	0	0	0
3	40	36	35	3425	875	25.54	722	21.08	5	.15	18	.53	130	3.80
4	22	20	9	2024	225	11.11	55	2.72	5	0.25	165	8.15	0	0
5	35	35	28	2618	934	35.68	335	12.80	210	8.02	32	1.22	357	15.93
6	20	20	18	1990	1547	77.74	189	9.50	190	9.54	3	0.15	1165	58.54
UNK*	7	7	3	311	156	50.16	2	.64	65	20.90	0	0	89	28.62
	153	133	103	12668	3791	29.93	1356	10.70	476	3.76	218	1.72	1741	13.74

* Insufficient information for category assignment
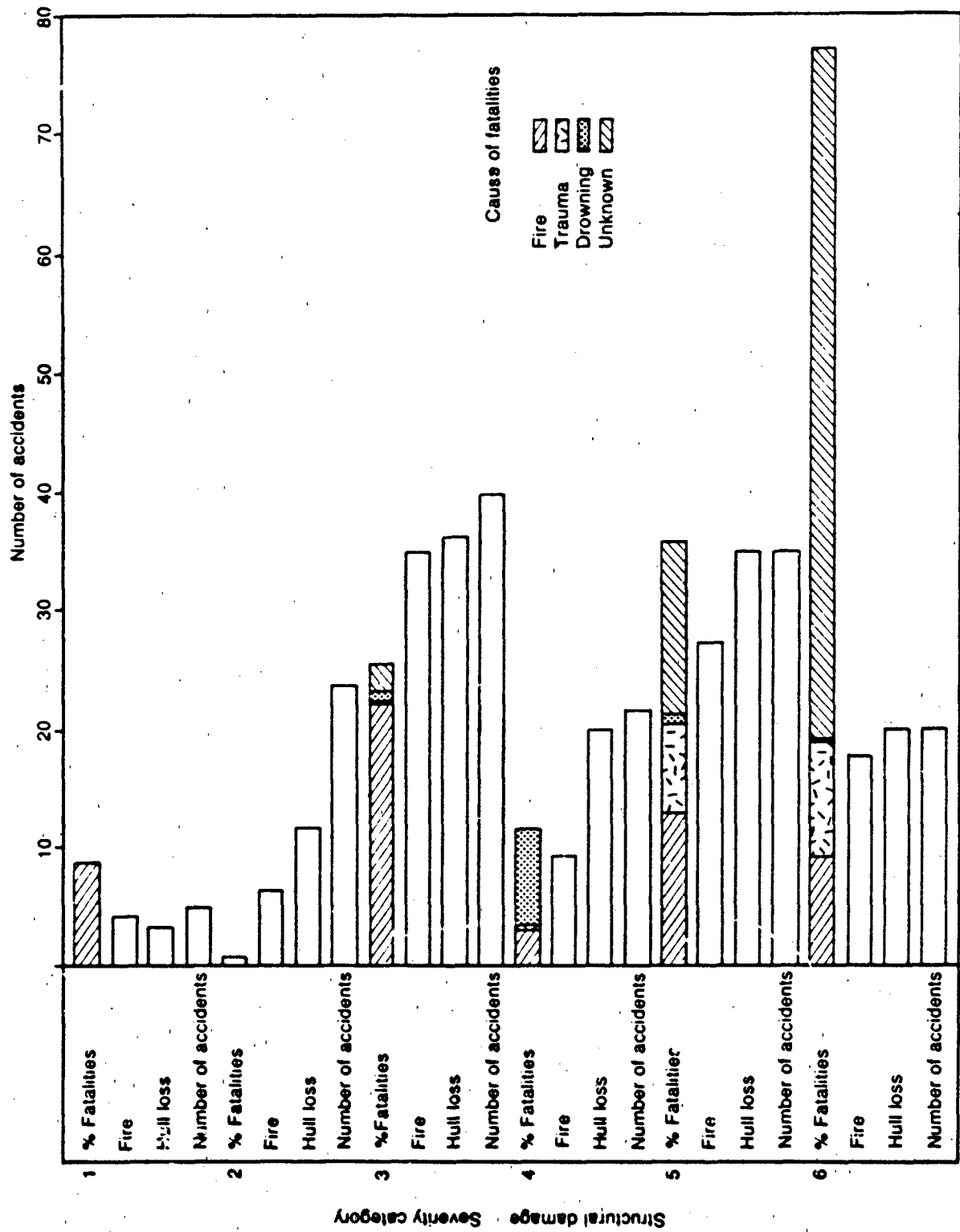
Figure 4.1–Accidents by Category

rate. Little structural or detailed information is available on several accidents in which a large percentage of the occupants perished. Water impact usually results in severe damage to the lower fuselage, often accompanied by class 2 breaks in the fuselage and separation of wings, engines, and landing gear. In some cases many occupants drowned after evacuating the aircraft. In some cases the high fatality rate was due to inappropriate action of the cabin crews after the aircraft came to rest.

Last, as might have been anticipated, the overall survivability generally decreases as the major structural damage to the aircraft increases. For categories 5 and 6, known fatalities due to fire and to trauma appear in almost equal numbers. While these categories also have the largest percentages of undefined fatalities, it is not expected that the results would be changed if a full definition of fatalities were available.

Category 1 accidents experienced only minor structural damage. There were three hull losses and 53 fatalities due to fire. Two accidents involve fires, caused by separation of an engine, that resulted in a catastrophic explosion of the wing tanks. In both instances, fatalities occurred when tanks exploded while the aircraft were being evacuated. Another accident involved a fire due to penetration of the wing tank by debris thrown up from landing gear. In this instance the aircraft was successfully evacuated but was destroyed by fire.

Category 2 accidents involve only one fatality. In this case the trauma fatality occurred as the aircraft penetrated the airport terminal. The purser was killed when the hull was ruptured by a building column. This accident is an anomaly. There are 12 hull losses, 2 of which were due to slowly spreading fire. Two accidents involved engine separation and fuel line fires while another accident was a friction fire due to nose gear collapse.

Category 3 accidents involve at least 722 fire related fatalities and 5 trauma fatalities. There are three accidents involving 179 occupants and 130 fatalities that are undefined. The DC-8 Toronto accident was placed in this category because of the major fuel spill due to tank rupture as the engine/pylon separated. The 108 fatalities are treated as fire related because the wing fuel tank exploded in the air while attempting a go-around. The five trauma fatalities were in the KLM Tenerife accident; and were in the lower fuselage and were ejected. Drownings accounted for 18 fatalities, at least 15 of which occurred after evacuation.

Category 4 involves 225 fatalities of which 55 are from fires not due to tank rupture, 165 due to drowning, and 5 to trauma. One of these was the 727 Salt Lake City accident in which fire resulted from a hard landing that caused a ruptured fuel line.

In most accidents involving drowning, few details are available except for the DC-9 St. Croix accident. In this case the drownings are thought to occur after evacuation and trauma fatalities were due to seat separation due to floor distortion and to occupants who did not use the seat belts.

Category 5 involves 934 fatalities of which 45% are of undetermined causes. Of the known causes of fatality, 335 are related to fire and 210 are related to trauma. The 747 Pan Am Tenerife accident accounts for 36% of the fatalities, with 144 deaths of undetermined cause. In this accident trauma fatalities were due to the destruction of the upper aft fuselage by the KLM 747 and the entry of the KLM engine pod into that section of the aircraft. Further, burning fuel from the Pan Am ruptured wing was sprayed into the area trapping most of those not killed by trauma. The four known trauma fatalities in the 727 Cincinnati accident were due to complete destruction of the cockpit area. The 10 trauma fatalities in the DC-8 Portland accident were due to intrusion of a large tree into the forward fuselage.

Category 6 involves 1547 fatalities of which 59% were of undetermined causes. Of the known causes of fatality, 189 are related to fire and 190 are related to trauma. In four accidents, only the fate of the flight deck crew is defined although there are indications of cause with terms as "many" or "most". The enormity of many accidents and shortage of pathological skills preclude accurate postmortem determination of cause.

RELATIONSHIP BETWEEN SCENARIO AND ACCIDENT SEVERITY CATEGORIES

Combining the structural damage severity category with the scenarios shows scenario development should include accidents having severity categories of 3 through 5. Category 6 accidents represent consumption of all the aircraft's protective structure. However, provisions made for less severe accidents would tend to improve the crashworthiness in some areas even in category 6 accidents.

Consequently, research efforts should be directed towards better defining the crash scenarios to represent this severity range. The improved definition includes initial conditions, aircraft motions, hazards encountered, and crash response of the systems. Methods of simulation should be developed that permit study of the parameters that affect the crash response so that these might be subjected to a more thorough engineering treatment.

INTERACTION OF STRUCTURAL COMPONENTS AND AIRCRAFT SYSTEMS

Most substantial damage or hull loss accidents that are impact survivable will involve damage, destruction, or loss of one or more structural components and aircraft systems. During the sequence of events as the destruction occurs and the aircraft come to a stop, the lives of persons onboard are being jeopardized. In the 153 accidents reviewed in this study, it was determined that the most critical event in the sequence that caused most fatalities was the releasing and ignition of fuel which then developed into severe fires. For those persons not injured by impact, the probability of survival was determined by time (measured in minutes and seconds) and by the impediments in the escape route. In order to define approaches to improve the crashworthiness of transport aircraft it is necessary that the involvement of the structural components, systems, and subsystems be determined and the sequence of events and interaction of their involvement in a variety of accidents be well understood.

Discussion of the major hazards, the dominant structural components, and the interaction as relating to survivability is provided in the following sections.

WING BOX — INTEGRAL FUEL SYSTEM

Severe fuel fires, that are the primary cause of most fatalities, result from unwanted release or spillage of tank fuel. In this study it was found that 107 accidents involved tank fuel spillage and 85 of these had fires of varying severity. Spillage directly from the integral tank usually occurs from six types of events: wing box fracture or break, lower wing skin tear or rupture, penetration of the tank by an object, tearing open the wing box during separation of main landing gear or engine pylon, fuel tank ullage explosion, and flow from wing tip vents. In a given accident two or more of these types of spillage sometimes occurs. These types are shown in figure 4.2.

Fuel spillage due to wing break occurrences have been assessed with regard to incidence of fire and fire related fatalities. The area of the spill has been assessed where "large" is 30 meters or larger in diameter, "medium" is 10 to 30 meters in diameter, and "small" is under 10 meters. Fire intensity has been assessed with respect to consequences of fire as large, medium, or small. Interaction of fire with fuselage in terms of fuselage entry and of effect on evacuation also have been assessed. Fire entry to the fuselage has been gaged as entry through breaks or as burn-through. In addition, the effect of fire on the postcrash evacuation has been assessed. Here, large effects implies some fire related fatalities, while small implies some hindrance.
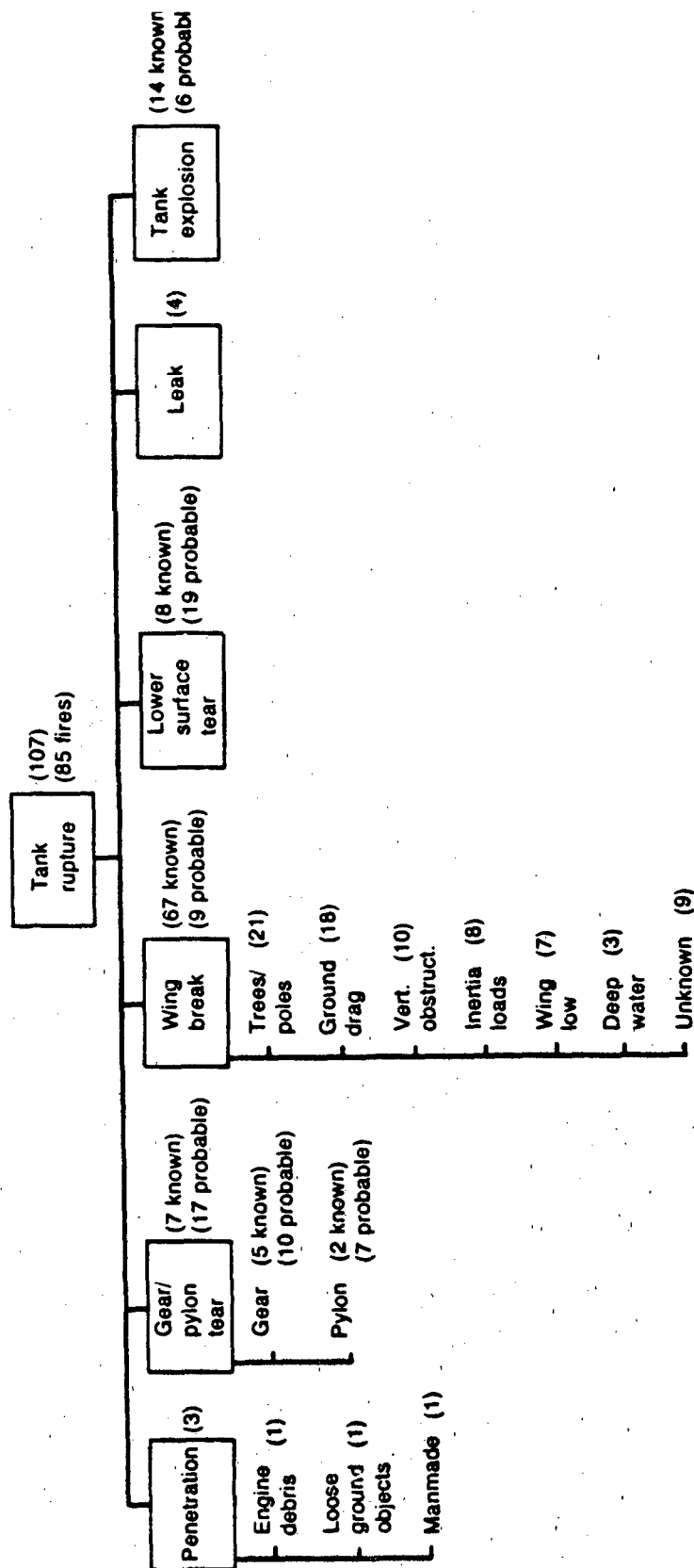
Figure 4.2—Types of Tank Rupture

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maintenance of the wing ground clearance and to transmission of loads to the wing structure (only for wing pod mounted engines).

WING BOX BREAK/FRACTURE

In 67 accidents, fuel spillage occurred when the wing box fractured due to excessive forces or loads. There are also nine other accidents in which it is believed that wing fracture occurred but insufficient detail is available to define other factors.

Most fractures occur due to high vertical loads or due to impact with large objects such as trees, buildings, or embankments. In some cases the landing gear and engines may also collapse or separate at the time wing fracture occurs, however the gear and engine generally have little influence on the severity of the accident except possibly by providing an ignition source for the spilled tank fuel.

Some wing fractures occur early in the accident sequence and the fuselage continues to slide or move, possibly away from the initial large fuel spill location. Fuel is usually scattered over a large area. In other cases the wing fracture occurs at about the time and point where the aircraft comes to rest and the fuel spill is adjacent, under, or around the fuselage. If fuel ignition occurs, an almost instantaneous severe fuel fire develops; this constitutes the "most hazardous scenario." Damage to other structural components can influence passenger/crew survivability in this situation. Fuselage breaks and fuselage lower surface ruptures can provide immediate access for flame and smoke to the passenger compartment. Damage to the cabin interior such as collapsed overhead storage, galley debris, ruptured floor, and jammed/blocked exits can impede evacuation. The interactions of these structural components and the impact that each has on survivability in the wing break/severe fire occurrence, is different for each occurrence, no two are the same. From this study it is concluded that research should be accomplished in the area of wing box and integral tank design philosophy and in the development of wing structure that will minimize wing tank fracture when wing box breakage or separation occurs.

Results of these assessments are shown in figure 4.3. Some general observations may be made. First, wing breaks result in a high percentage of fires (deep water impact being an understandable exception). Second, wing break accidents have a high fire related lethality. Third, if fire is present it is highly probable that fire will enter the fuselage either through a fuselage opening such as a door, break, or by a burn-through. Fourth, the presence of fire has a serious effect on the postcrash evacuation. Breaks due to impact in deep water have not experienced fires although hazard of fire is present. Breaks due to dragging the wing across the ground appear to result in a lower percentage of fatal accidents than other types of breaks.

Wing breaks due to impacting trees/poles and like obstructions are particularly severe types of breaks with regard to size of the spill and resulting fire and incidence of fire related fatalities. For 21 accidents, large spills occurred in at least 16 with fires occurring in at least 15. Fire related fatalities did not occur in only seven accidents. It may also be seen that fire entry through fuselage breaks occurred in almost 60% of the accidents while entry by burn-through occurred in about 10% of the accidents. Fire was a factor in evacuation in about 30% of the accidents. For this type of break, interaction with landing gear and with engine/pylon separation appears quite small as might be expected.

Similar assessments may be made for other causes of wing break with similar results. An exception is the effect of gear separation and engine/pylon separation for the ground drag break. Here the

Figure 4.3–Wing Break Assessment

Number of accidents
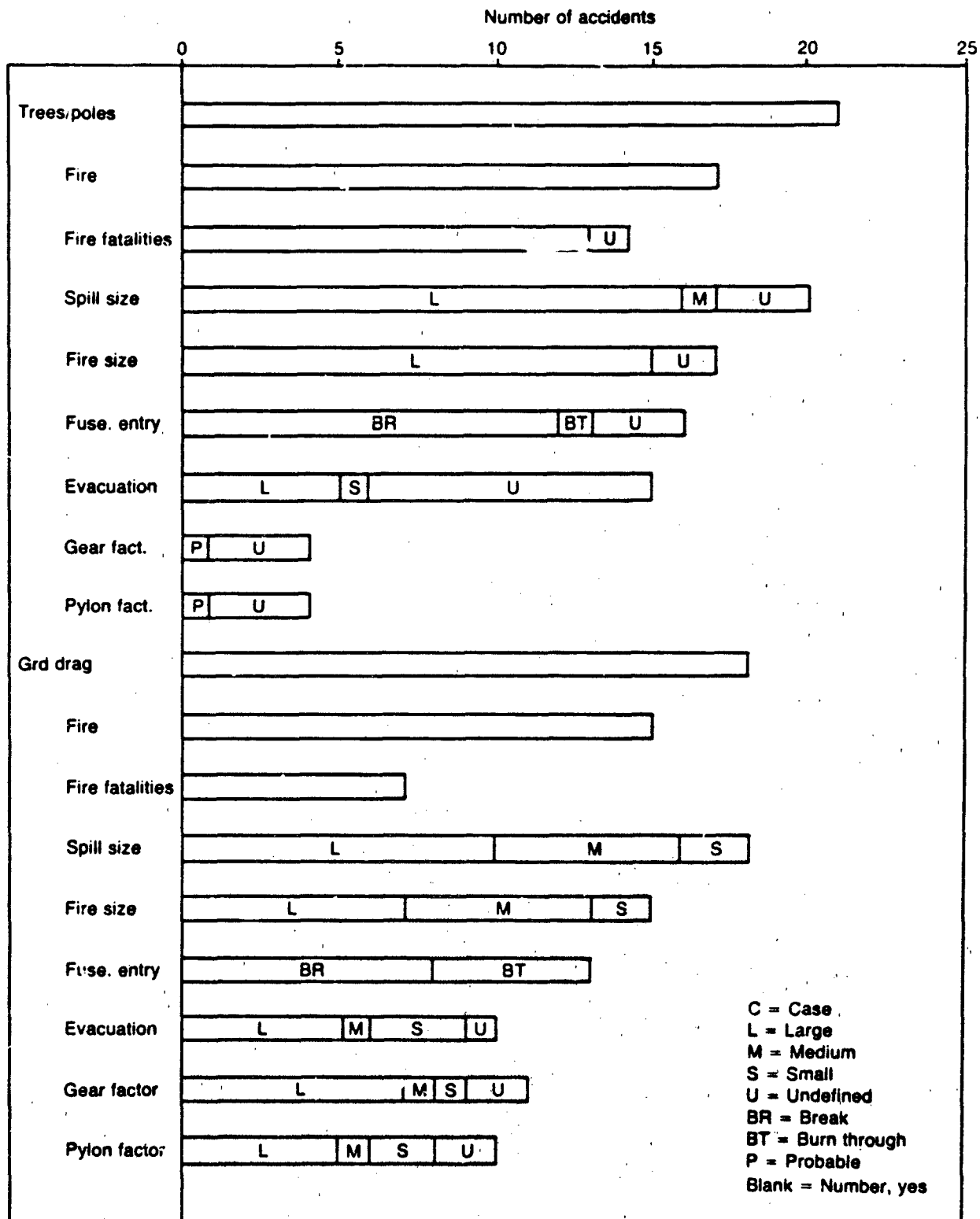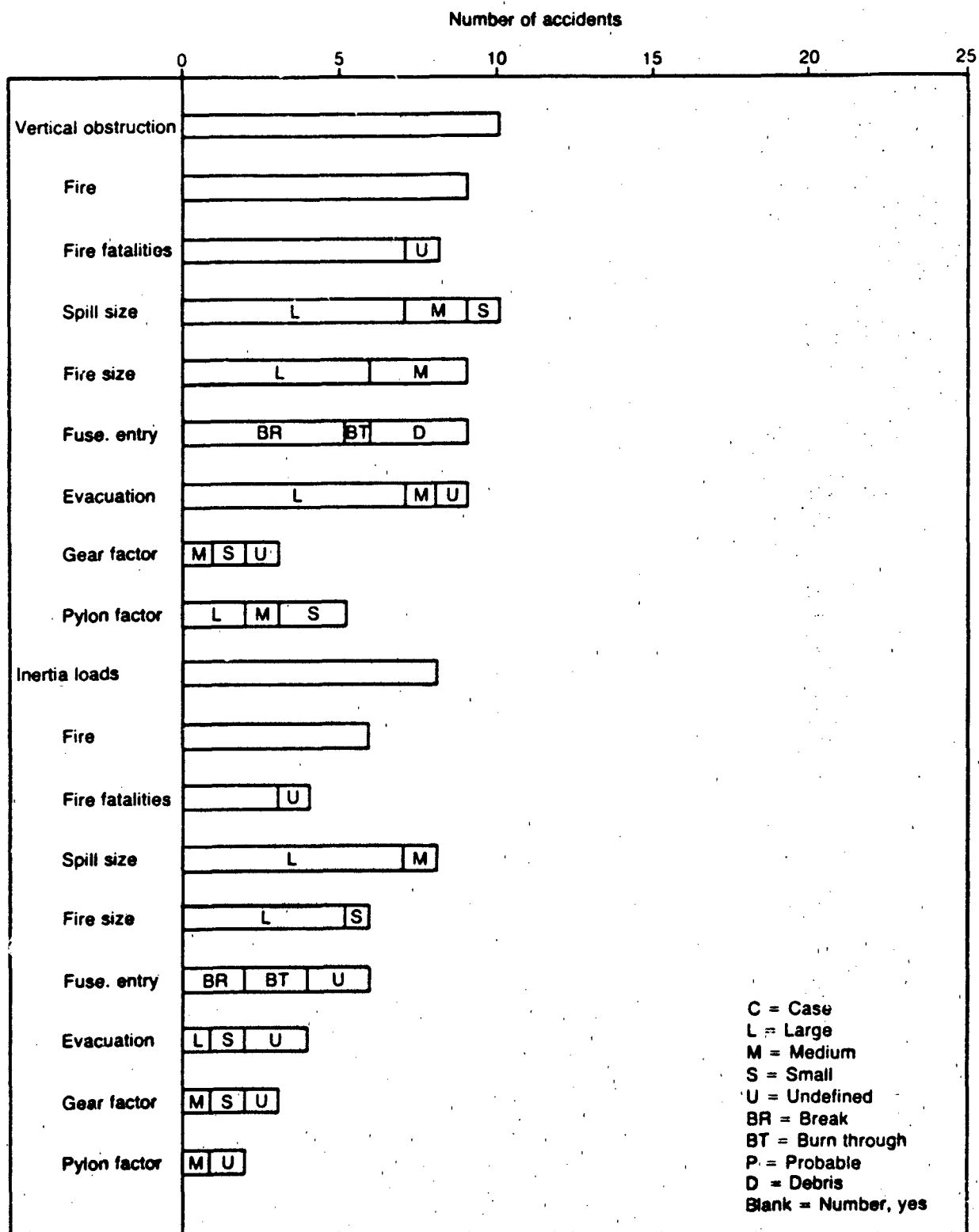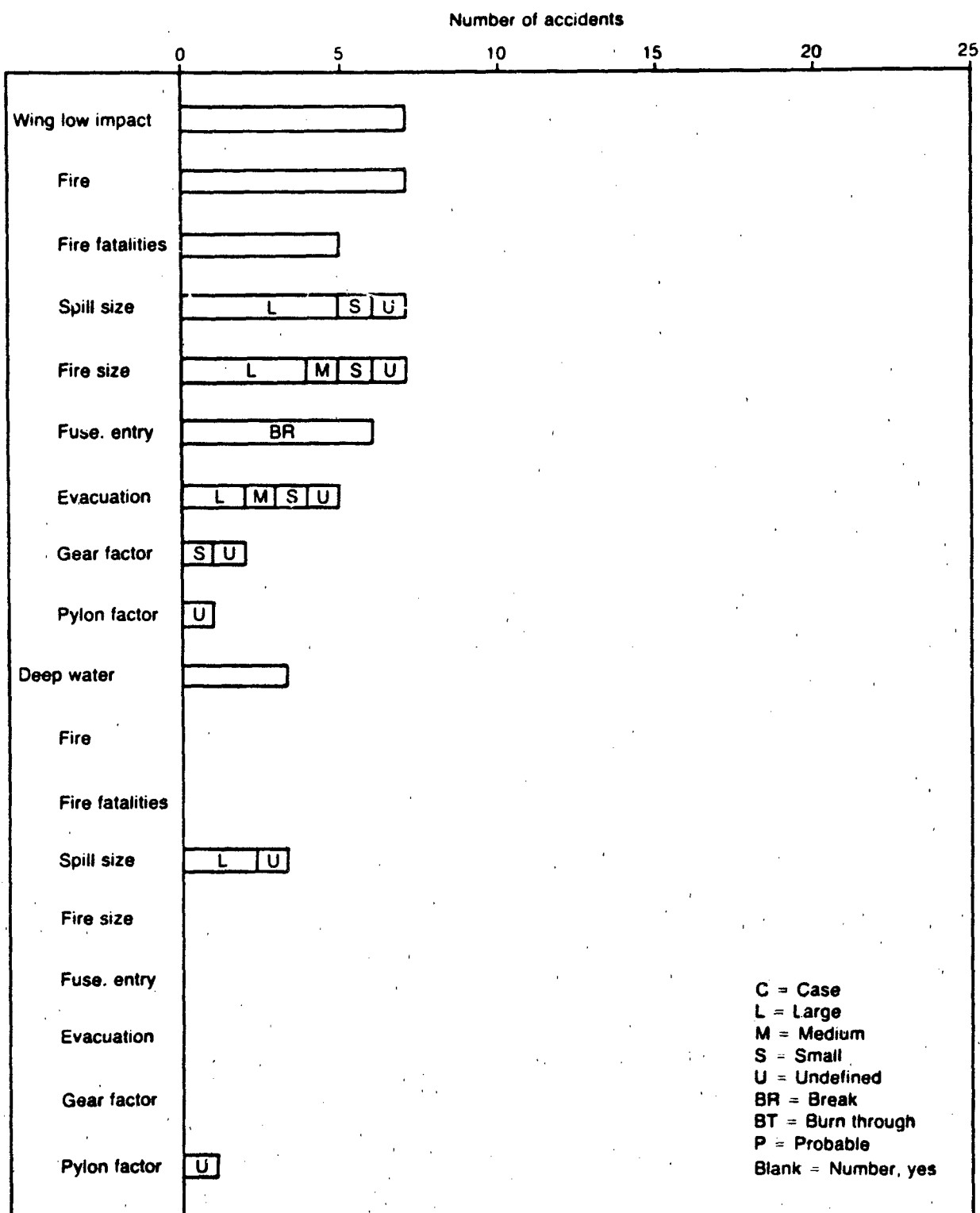
Figure 4.3 – Wing Break Assessment (Continued)

Figure 4.3–Wing Break Assessment (Continued)

Number of accidents

| | 0 | 5 | 10 | 15 | 20 | 25 |

Undefined

Fire

Fire fatalities — C | P | U

Spill size — L | U

Fire size — L | U

Fuse. entry — BR | U

Evacuation — U

Gear factor — U

Pylon factor — U

C = Case
L = Large
M = Medium
S = Small
U = Undefined
BR = Break
BT = Burn through
P = Probable
Blank = Number, yes
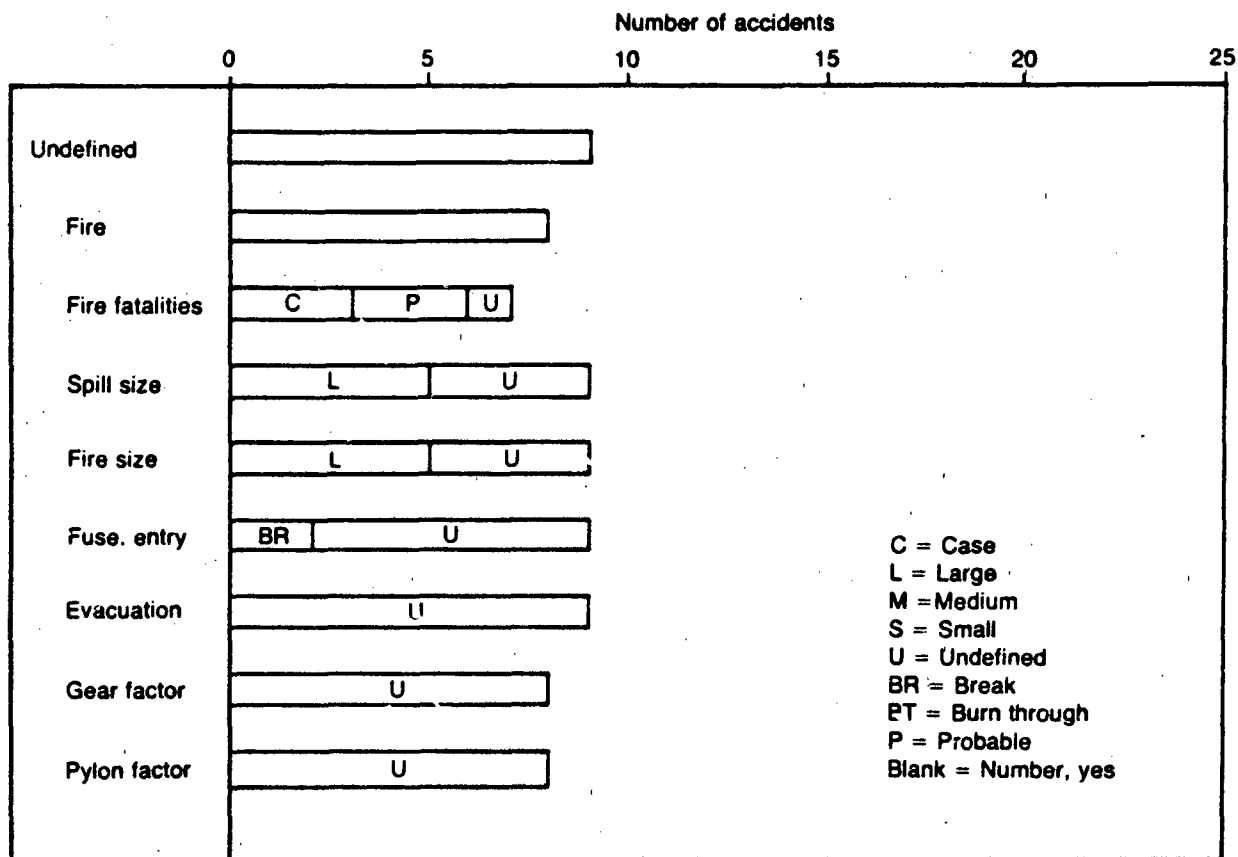
Figure 4.3–Wing Break Assessment (Concluded)

crash role of gear and wing/pylon mounted engines in maintaining ground clearance of the wing does appear to be a significant factor. If a gear more tolerant to separation or collapse were available, some improvement in crashworthiness might be achieved.

WING LOWER SURFACE TEAR/RUPTURE

In this study, tear or rupture of the wing lower surface is known to have occurred in eight accidents and probably occurred in 19 others. These generally occur when the wing is subjected to scrubbing/sliding on the runway, on rough terrains, or over various objects. Records indicate that 13 involved contact with rough terrain, 7 involved sliding over fences and walls, 4 involved sliding on level ground, 1 involved settling on a separated engine, and 1 involved impact with another aircraft. In 26 of these accidents the aircraft was destroyed and 40% had fire related fatalities.

The hazard evolving from these wing tank tear/ruptures is related to the size of the tank opening, the rate at which fuel is released, the temperature, and if the fuel was ignited. Many of these occurrences involve severe fires, however they tend to be localized in the wing area and thereby make it possible for persons onboard to evacuate from both ends of the fuselage away from the fire. The interactions and impact that other structural components have on these wing lower surface tears is the same as with wing break occurrences. An increase in the hazard occurs with time (possibly 30 seconds to 5 minutes); fire impacting on the wing often causes tank explosions that spread the fuel further and intensify the fire. Research should be directed in the area of containing the fuel within the tank or at least restricting the flow of fuel through the rupture or hole in the wing skin.

Assessment of these accidents is shown in figure 4.4. As may be seen, lower surface tear results in large fuel spillage with the fire being severe. In about 60% of the spills, fire enters the fuselage by burning through the skin, while fire entry through fuselage breaks occurs in 15% and by other routes in about 10%. Fire has affected evacuation in 40% of the cases.

With regard to the interaction of landing gear collapse or separation, gear has been a major factor in 50% of the spills and had a lesser effect in about 30% of the spills. Wing mounted engine/pylon separation or collapse during lower surface tear failed to maintain ground clearance in 95% of the cases.

Wing Box Tear

Tearing away sections or parts of the wing box fuel tank and subsequently releasing large quantities of fuel during separations of main landing gear or of engine pylon is an infrequent occurrence, being reported in seven accidents. However, when it does happen, a severe fuel fire generally occurs. Design philosophy for main landing gear and engine pylon attachment to the wing box should be reviewed to ensure these units are fused for a clean overload separation that does not fracture the integral fuel tank. Assessment of wing box tear is shown in figure 4.5.

Tank Ullage Explosions

Wing box fuel tank ullage explosions have been reported in 17 accidents and probably occurred in 6 others. In most of these, a severe fire already existed and generally the size or intensity of the fire increased. In most cases it is not known how many, if any, additional fatalities resulted from the tank explosions but it appears from available data that evacuation was usually affected. The initial fire in three accidents occurred at the engine pylon wing interface after engine separation, two of these explosions occurring in flight. Research should be directed towards development of devices, systems or procedures that will eliminate or reduce the probability of ullage explosions. However, reliability of the fuel delivery system must not be compromised or reduced to achieve the elimination of ullage explosions. Assessment of tank ullage explosions is shown in figure 4.6.

Figure 4.4–Lower Surface Tear

Number of accidents

Lower surface tear
Fire
Fire Fatalities
Spill size
Fire size
Fuse. entry
Evacuation
Gear factor
Eng/pylon factor

C = Case
L = Large
M = Medium
S = Small
U = Undefined
BR = Break
BT = Burn through
P = Probable
Blank = Number, yes
D = Door

*Eight A/C had no wing pod mounted engines
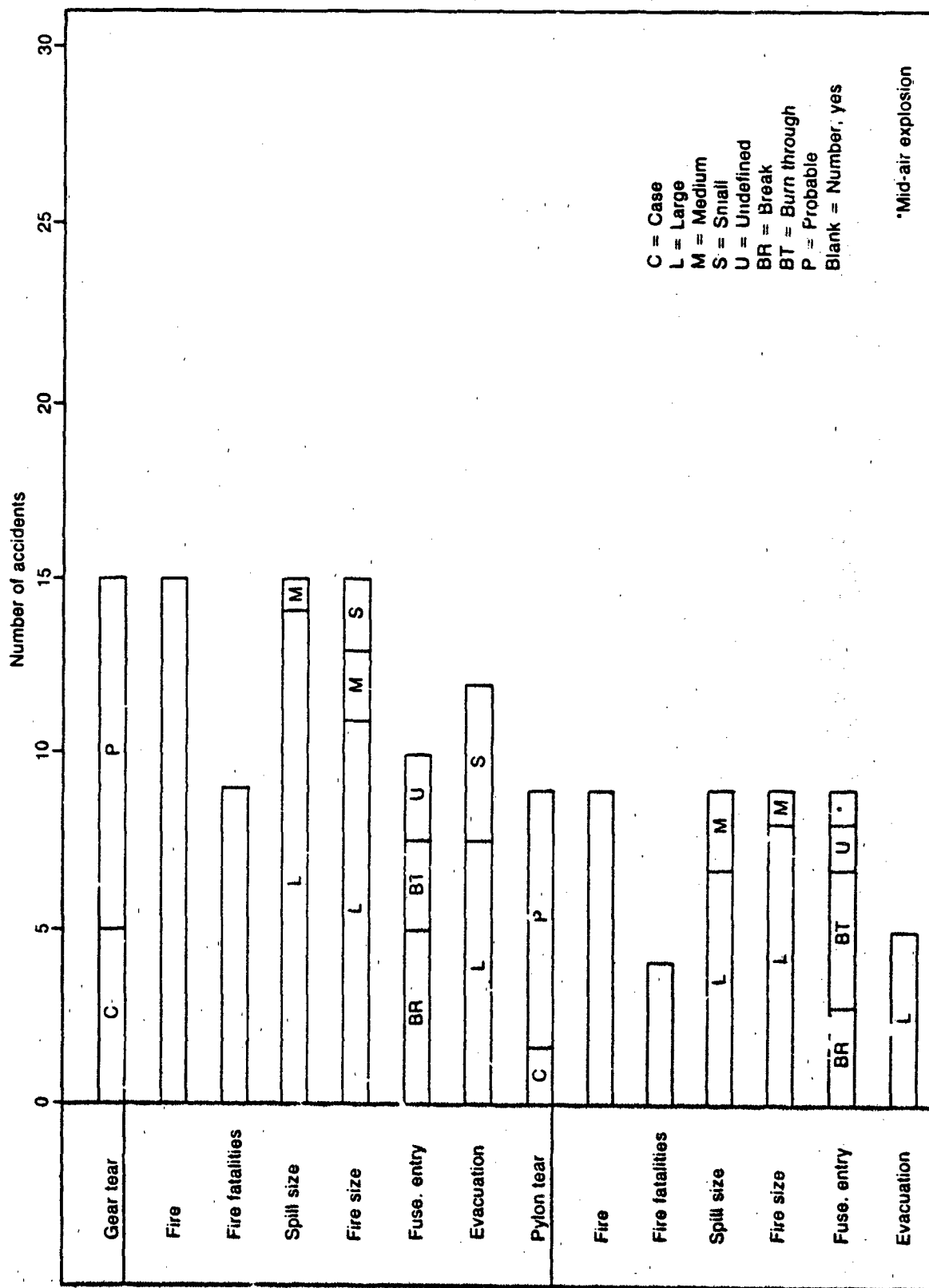
Figure 4.5–Gear/Pylon Wing Box Tear
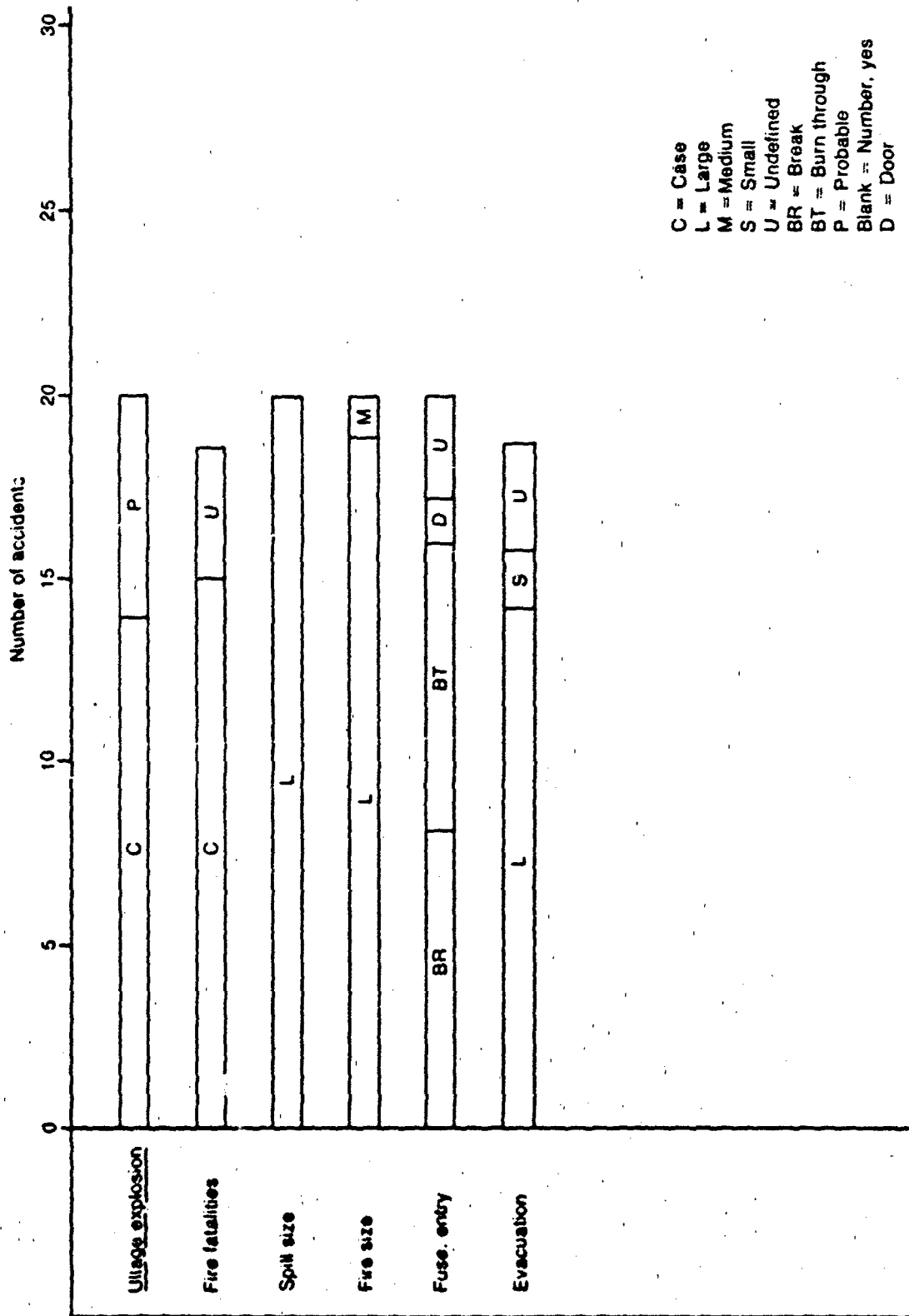
Figure 4.6–Ullage Explosion

Wing Tank Vents

The wing tank vent system has been involved in one severe fire accident. In this case, a 707 in Rome, an engine fire spread to fuel dripping from the adjacent wing tank vent at the wing tip, progressed through the vent system and caused a tank ullage explosion. Any studies involving fuel tank design should include the tank vent system and flame suppression.

Tank Puncture

There are three accidents in which tanks have been punctured by foreign objects. Two of these accidents occurred during aircraft operation and resulted in fires that destroyed the aircraft but for which there were no fatalities. One of these involved puncture by debris from a disintegrating engine and the other involved parts from a disintegrating wheel. The third incident occurred after the accident when the tank was punctured during rescue operations but there was no fire.

Leakage

There are four accidents in which fuel spillage resulted from leaking tanks. Only one accident experienced fire which destroyed the aircraft, but there were no fatalities. While fire hazard is present these accidents have not been lethal.

Body Lines

Rupture of body fuel lines is a hazard associated with aircraft configurations having aft mounted engines or auxiliary power unit. If fuel tank shut-off valves are activated immediately after a crash, the amount of fuel spilled due to body line rupture is only a minor contributor to the accident severity. However, when the lines are not shut off, the resulting fire has been catastrophic.

The "classic" case of this was the 727 Salt Lake City accident on November 11, 1965, in which a separated landing gear penetrated the lower fuselage and ruptured a body fuel line. Forty-three occupants died from fire related causes. As a result of this accident, body lines were strengthened and rerouted to avoid this type of rupture. The only other instance in which body lines are thought to be a major contributor to the severity of an accident is the DC-9 O'Hare on December 20, 1972, where the aft fuselage of a DC-9 struck the vertical tail of an 880 during take-off and probably ruptured a body fuel line. Ten persons perished from fire related causes in this accident.

Assessment of body fuel line rupture is given in figure 4.7. As may be seen, there are 10 accidents with 4 probable instances of rupture. Fire was present in each instance with fire related fatalities in nine accidents. Fuel line rupture fires are deemed to have been a factor in evacuation in possibly six of the cases. Fuselage breaks were present in eight of the cases with fire entering the fuselage through the breaks in six cases. Fire came through the floor in three cases with one uncertain.

SEATS

Seats interface with the occupant and with the structure to which they are attached. In assessing these interactions, the relation of the seats and the structure is treated first, and the relation of the seat to occupant is treated second.

Three basic types of seats are of concern: crew seats, flight attendant jump seats, and the passenger double and triple bench seats. Crew seats are single seats that are mechanically adjustable to facilitate operation of the aircraft and attach to the cockpit floor structure. A combination shoulder and lap belt restrain the occupant. Flight attendants' jump seats may be single or double units attached to a bulkhead and mechanically folded or retracted when not in use.
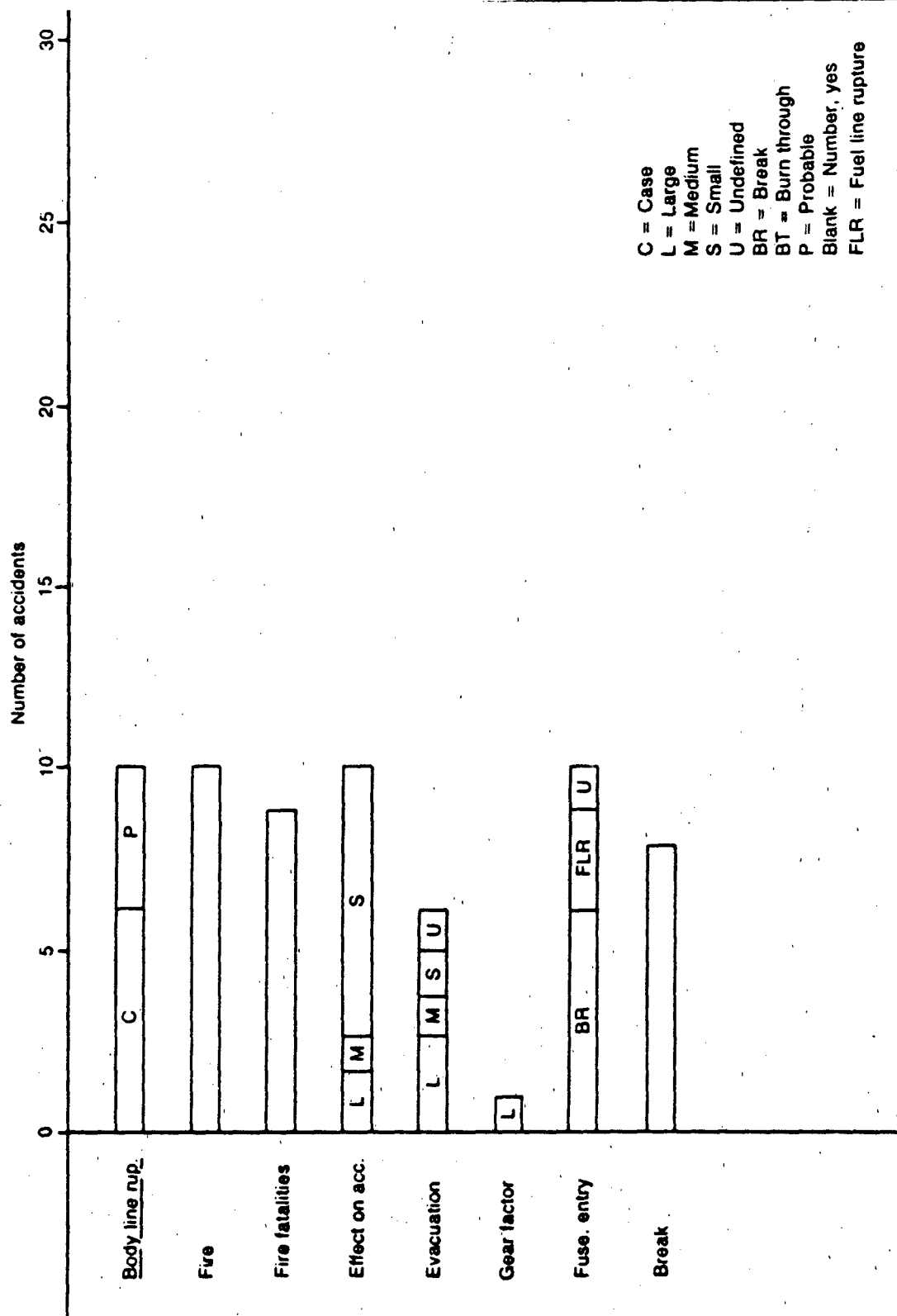
Figure 4.7–Body Line Rupture

These seats support vertical loads, with the restraint harness transmitting side and longitudinal loads to the structure. Passenger seats are attached to floor tracks and in some designs to the fuselage sides. Floor tracks are attached to the floor structure or to pallets attached to the floor structure. The passenger is restrained by means of a lap belt.

For the interaction of seats with structure, no distinction is made for types of seats, but two interactions are of concern with the structure — the effect of a fuselage break and the distortion of the floor. In a fuselage break, seats may be ejected through the break, or may simply separate from a broken floor track. In floor distortion, seats may separate from the track, or may be elevated.

The potentially most lethal of these interactions is ejection through the fuselage break. Survival of the occupant is a matter of chance, depending on many factors such as velocity of ejection, nature of impact area, and the orientation of the occupant at impact. Further, the ejected occupant may be in an area that is exposed to fire or is overrun by the advancing aircraft.

Seats located in the vicinity of a fuselage break may be subject to high acceleration pulses due to the redistribution of the stored strain energy as the structure breaks. This frequently results in the separation of the seats due to rupture of seat tracks, seat track attachments or seat structure. Separated seats may then shift position and cause injury or hinder the egress of the occupant.

Seat dislocation from floor distortion may be due to separation or to elevation of the seat. Separation may force the occupant to contact interior objects and may hinder egress. Floor elevation may block egress routes such as over-wing escape hatches, may hinder the occupant in exiting from the seat, or may force contact with the cabin interior. For crashworthiness, it is desirable to keep seats attached, in place, and to maintain a survivable volume for the occupant.

There are 48 accidents with identified interactions and another 21 accidents to which probable interactions were assigned. Assessment of these accidents is shown in figure 4.8. Fuselage break has resulted in 15 certain accidents with one or more occupant ejected through the break, and probably at least two more. Separation of some seats at the break with the seats remaining in the aircraft has occurred in 30 accidents with probable occurrence in at least 13 other cases. Seat separation due to floor or fuselage side distortion has occurred in 19 accidents with probably 5 other cases. Elevation of the seat without separation has occurred in 14 accidents with probably 4 other accidents.

The discussion of seat/restraint performance in survivable crashes is presented in two parts. The first part includes those accidents in which injuries that might be related to seat strength performance and in which seat/restraint performance are cited by the accident investigation team. The second part includes serious accidents in which the seat/restraint performance was not cited and in which no injuries that might be related to seat strength occurred.

Only 31 such accidents could be found in which seat performance was mentioned in NTSB reports. A detailed review of these accidents indicates seats certified to current FAR seat strength criteria provide protection to the occupant commensurate with the crash loads. The aircraft strength and occupant injury tolerance capability appear to be in proper balance.

A separate independent study of this matter conducted within the FAA is contained in reference 1.

The current study drew upon NTSB accident reports and special studies, NTSB Human Factors Factual Reports, NTSB Public Hearing Dockets, and the manufacturers accident files for each accident. The separate FAA study also treats NTSB data, and includes FAA Civil Air Medical Institute (CAMI) data but does not include the manufacturers files.

Number of accidents

70

60

50

40

30

20

10

Total cases — C | P

Ejected thru break — C | P

Separation at break — C | P

Sep. at floor distortion — C | P

Elevation at floor distortion — C | P

C = Case
L = Large
M = Medium
S = Small
U = Undefined
BR = Break
BT = Burn through
P = Probable
Blank = Number, yes
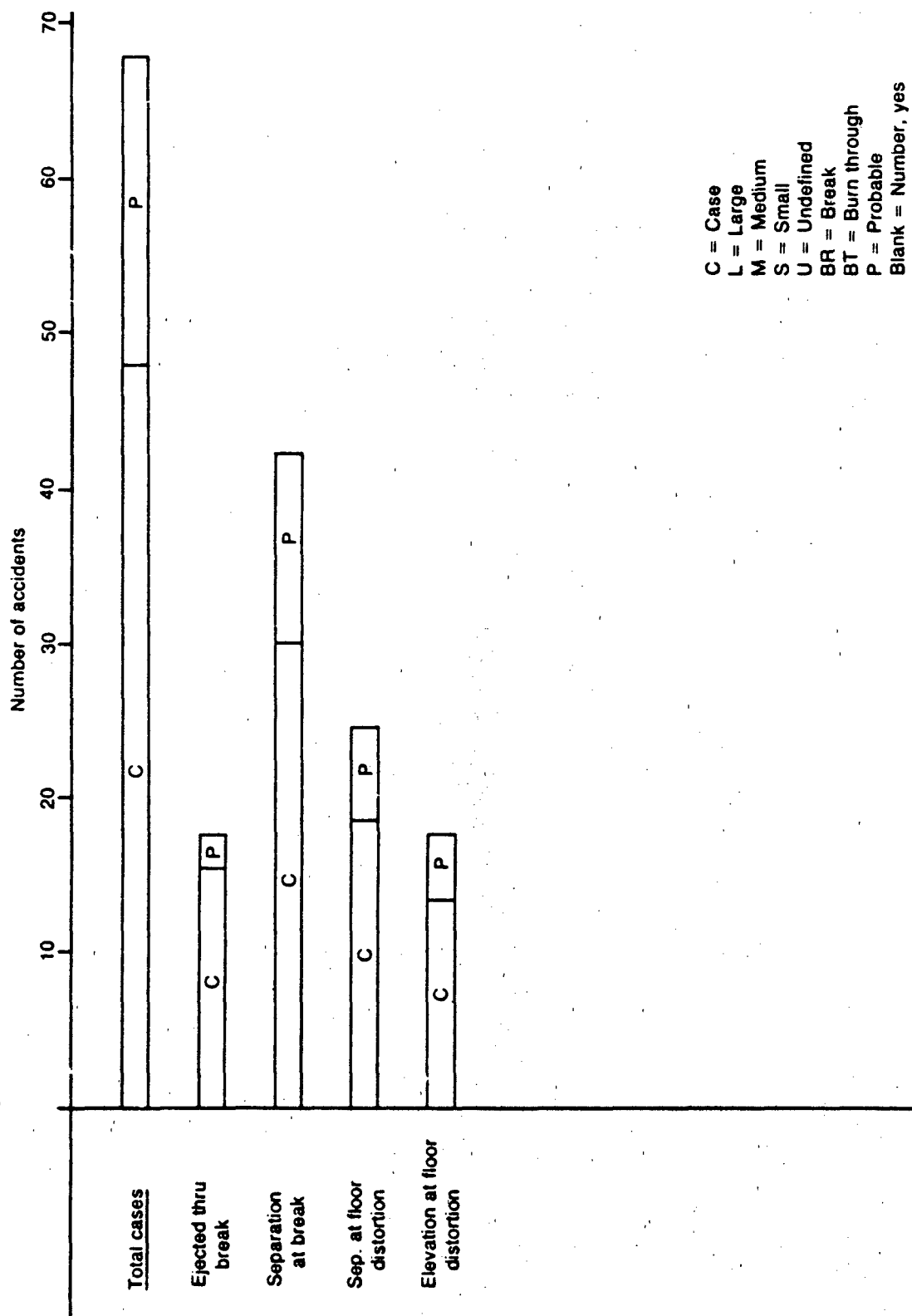
Figure 4.8–Seat Interactions

For engineering purposes it is necessary to relate seat performance and injury. To do this it was necessary to review the Human Factors Factual Reports and, in some instances, survivor testimony. The NTSB statistical category, "Serious Injury" (see app. A), used in NTSB Accident Reports does not necessarily identify actual physical injury nor relate injury mechanism to injury. Accident victims who are hospitalized for 48 hours for medical observation, legal considerations, or other reasons are listed as serious injuries even if there is no treatment. An immediate improvement in crashworthiness statistics could be obtained simply by using a more accurate definition of serious injury. To rely on these injury statistics may lead to exaggerated conditions and produce erroneous conclusions.

Reference 1 identifies 27 ground impact accidents including 7 propeller-driven aircraft and 20 jet transport aircraft. A comparison of those study accidents with this study shows that 18 of 20 jet transport accidents are included in the present study. The two accidents omitted are the DC-8 JFK accident on September 15, 1970, in which the seats performed adequately and no occupant was actually seriously injured, and the 707 Pago Pago accident on January 30, 1974 in which no seat performance was cited. The additional accidents in the present study include accidents prior to 1970, two Canadian accidents, and the 747 Japan Airlines accident in Anchorage on December 16, 1975.

In these accident reviews, investigators did not identify a single trauma fatality caused by lack of seat strength or seat attachment structure strength. It is recognized that such identification is difficult because of incomplete knowledge of local crash dynamics, fatal injury mechanisms, and survivor testimony as to his experience. Also, postcrash fire frequently consumes necessary evidence. There are limited, though subjective, indications where an increase in attachment strength may have provided some benefit. For instance, one passenger in the 727 St. Thomas accident was ejected in his seat through a fuselage break and died of trauma injuries. This seat was located in the aircraft in the region of fuselage destruction and there is no assurance that any increase in seat strength requirements would have provided any benefit.

While it can be observed that injuries were sustained in deforming the seats, no sequence of events has been identified where increased seat strength would have reduced occupant injury. Consequently, the cases presented in table 4.6 involve serious injury and/or seat/restraint system crash performance for accident survivors. Twenty-six accidents involve a hull loss, 19 involve fire, 22 involve at least one fuselage break, 14 involve severe floor distortion, and 4 involve water impact. Thirteen accidents are only partially impact survivable since survivable volume for at least one occupant was lost. For seat/restraint system strength performance, injuries to the head, spine, chest, and pelvis are of concern, although injuries of these types may arise from a variety of other causes. These are shown for the flight deck crew and passengers, while spine and pelvis injuries are shown for flight attendants.

Table 4.6 also shows seat performance for seat-to-floor attachments, seat legs, seat pan, and restraints for flight deck crew and passenger seats. The number for attachments and seat legs are for seat units. Flight attendants' jump seat structures, mechanisms, and harnesses are also identified.

Some general observations may be made in reviewing these accidents. First, there is evidence of spinal injury for flight deck crew, flight attendants, and passengers where no seat crash performance was cited by the NTSB. In addition, there were spinal injuries to occupants where seat crash peformance was cited. If the injury tolerance of these people is exceeded by the crash forces transmitted by seats designed to current strength requirements, increasing the seat strength criteria would do nothing to improve their protection. Second there are instances where seat performance was cited in which no serious injury was incurred suggesting that increasing seat strength might transmit sufficient load to produce serious injury, a negative benefit.

Table 4.G—Cases Involving Injury Only

				Injuries												Seat/Failures															
				Flt. Deck			PAX			F/A				Flt. Deck Seat				PAX				Seat				F/A				PAX		
Notes	Hull Loss	Occupancy	Fatalities	Serious Injury	Spine	Pelvis	Chest	Head	Spine	Pelvis	Chest	Spine	Pelvis	Chest	Seat Pan	Legs	Seat	Harness	Seat Pan	Legs	Attach	Mech	Harness	Seat Pan	Attach	Legs	Mech	Survivability	Hull Break	Floor	Water

NOTES:

1. CREW DID NOT USE HARNESS
2. SEVERE LOSS OF STRUCTURAL INTEGRITY
3. BOTH NOTES 1 AND 2 APPLY
4. PAX RECEIVED BROKEN ANKLE DUE TO SEAT MOVEMENT (PARTIAL FAILURE)
5. PAX (SEAT 6A) DIED — INJURIES INCLUDING TRANSVERSE FRACTURE OF BACK. PAX (SEAT 7A) DIED — STRANGULATION. NOTE 2 APPLIE
0. INDICATES NO OCCURRANCE
S. INDICATES SURF.
OTHER SYMBOLS ARE PLACEHOLDERS

64

Seat detachment (separation) is generally associated with loss of structural integrity due to destruction of the fuselage shell, fuselage breaks, and to extreme distortion of the structure. Detachment may occur if all the seat legs or attachment fittings rupture or if the seat tracks rupture. This indicates that a more compliant seat/floor substructure to accommodate distortion might be more beneficial than an increase in seat strength criteria.

For commercial jet transport aircraft, there is little evidence of seat separation with subsequent "stacking" in the forward section of the aircraft. Two exceptions to this are the DC-9 St Croix accident where three double seats stacked due to the impact of some passengers who did not use their lap belts; and the 737 Midway accident where two triple seats (rows 14 and 15 A, B, and C) stacked due to severe structural damage to fuselage in that area. The more severe injuries occur in the vicinity of fuselage breaks and areas of extreme fuselage distortion. This might be expected since these are locations of very high loadings and areas where structure has lost its ability to protect the occupants.

Passenger Seats

In those accidents involving high longitudinal loading such as the 727 Cincinnati, 737 Midway, L-1011 Miami, DC-9 Boston, DC-9 Charlotte, 727 JFK, 727 St. Thomas, DC-9 New Hope, 737 Cranbrook, and the DC-8 in Portland, extreme destruction of the fuselage was experienced. Passenger seat separation was observed in the areas of destruction. An increase in seat strength criteria would not have reduced the injuries in these accidents.

Examination of those accidents involving extreme vertical impact velocities such as the DC-9 St. Croix, DC-8 JFK, DC-9 Akron, 727 Denver, DC-9 Philadelphia, and the DC-9 Toronto accidents indicates an increased number of spinal fractures as compared to the total data set. In the Toronto accident, the aircraft went over a 51-ft cliff at 46 KIAS, equivalent to falling from the top of a five-story building, having a resultant deceleration of 25 g. At Akron, the aircraft flew over a 38-ft, embankment at 86 mph impacting on a roadway. The Philadelphia, Denver, JFK, and St. Croix accidents had hard impacts combined with high forward speeds.

These accidents indicate that the current passenger seat vertical strength criteria are closely matched to the threshold of injury for the passenger population. Further seat deformations observed in some of these extreme accidents used much of the available stroke indicating that the limit of energy absorption within the injury load threshold is being approached. However, further research on the energy absorption aspect of crashworthy seats should be done.

The DC-8 Anchorage accident was an overrun during an aborted takeoff in which the aircraft encountered a deep ditch and hit a building and an antenna tower. The aircraft lost engines, landing gear, wings were separated and broken and the fuselage broke open. Many of the occupants left their seats and were standing in the aisles before the aircraft came to rest. Twenty-one spinal injuries occurred. One flight attendant and approximately five passengers are known to have sustained spinal injuries due to impact loadings. These five passengers were in seats that ejected from the aircraft when the fuselage broke. The remainder also may have occurred during impact or during evacuation, but there is no implication that increased seat strength would have provided more protection.

It may be seen that only four accidents are of concern in accident performance of the flight deck seats. In the DC-8 Portland accident, the right side of the cockpit experienced loss of survivable volume due to impacting a large diameter tree (of the cockpit occupants, only the Captain survived). The First and Second Officer's seats separated while the Captain's seat was attached but was loose and had some seat pan deformation.

In the DC-9 Philadelphia accident where the aircraft experienced a 10 g vertical deceleration, the Captain and First Officer seats experienced seat pan deformation. In applying loads to deform these seat pans both occupants experienced spinal injury.

In the 707 Kansas City accident one flight deck seat experienced seat leg deformation and the officer received a spinal injury. However, in this instance, it was noted that the harnesses were not used by the the occupants.

There are six other accidents in which spinal injuries occurred to flight deck crew but for which there was no seat performance cited. From this it may be concluded that seats are already stronger than pilots; and that further increasing the strength criteria for these seats would provide no benefit and might cause more severe injuries. It appears that some increase in energy absorption and load limiting might prove beneficial.

There are eight accidents in which flight attendants suffered spinal injuries while seated. In the DC-9 Anchorage accident, one injury occurred when the seat retracted from under the attendant during upward acceleration causing the attendant to fall to the floor. The remaining injuries occurred with the flight attendants in the seat. Two flight attendants had spinal and pelvic injuries in the high longitudinal deceleration 727 JFK accident on June 24, 1975, even though there was no damage to the seat/restraint system. Most of these citations involve instances of seat collapse or partial collapse due to rupture of a hinge, seat attachment fitting, or of the supporting mechanism. The injuries sustained did not cause loss of mobility in most cases.

There are instances where seat deformation contributed to harness problems, in that the flight attendant submarined after the seat pan deformed. The 727 Denver accident on August 1, 1975 is a case in point. The flight attendant suffered a back injury in this process. Also "some" spinal and pelvic injuries were experienced in the L-1011 Miami accident. Most of the remainder of spinal injuries occurred in hard vertical impact accidents with seat pan or mechanism citations. Also there are instances of seat deformation in which there were no injuries.

A review of accidents involving flight attendant seats indicates that increasing seat strength would not reduce the number of serious injuries. However, every effort should be made to include the results of TARC Project 216-10 study into flight attendant restraint design. Various government agencies such as the Army, Air Force, and the Department of Transportation have identified some levels of injury tolerance. See part of section 5.0 titled, Human Impact Tolerance for a more detailed discussion.

LANDING GEAR

There are 96 accidents in which one or more of the landing gear separated or collapsed. In addition there are 15 accidents in which the gear was stowed or retracted. The effect of gear separation or collapse will be considered, followed by the effect of gear in stowed positions. Some comparison of the two effects will be made.

Referring to table 4.2, the total occurrences show that for 95 cases of gear involvement (1 accident involves debris from the gear damaging the aircraft) there were 80 hull losses, 64 fires, 71 tank ruptures, 46 wing mounted engines/pods separated (11 cases of engine separation involve aft mounted engines), 62 fuselage breaks or crush, 38 door hatch involvements, 33 floor distortions, 33 cases of debris, and 26 seat citations.

In order to assess the role of landing gear and the interaction with other structural systems the accidents were reviewed. Direct effects of gear separation are: separation of wing pod mounted engines; rupture of fuel tanks by failing to maintain ground clearance and by the separating gear

tearing a wing box; and damage to the lower fuselage by crushing, friction, and by breaks. Secondary effects are fire due to fuel spillage from ruptured fuel lines and tanks and to friction, floor distortions, door/hatch problems, seat separation, and debris due to the distortion and breaks of the fuselage as a result of ground contact.

Figure 4.9 shows the assessment of gear separation. In 67% of the accidents all gear separated or collapsed, while in 22% only main gear separated or collapsed, and in 9% only nose gear separated or collapsed and in 2% nose gear and one main gear separated or collapsed.

Gear separation or collapse was involved in tank rupture in 17 cases of lower surface tear, 12 cases of wing drag breaks, 14 cases of wing box tear, and 4 cases of tank leakage. This fuel spillage resulted in 42 fires. Thus gear separation or collapse is a factor in 64% of the fires that occurred when gear participated in the accident. Using small, medium, and large as the degree of involvement, the gear was a large factor in 26 of the 42 fires, a medium factor in 4 of the fires, and a small factor in 12. With respect to fatalities, there were 28 accidents with fire related fatalities and 24 accidents with trauma deaths.

Lower fuselage crush occurred in 53 accidents with gear separation being a large factor in 37 cases. Lower fuselage crush has a secondary effect on door/hatch jamming, on separation of seats, and on cabin interior debris. Gear separation was a large factor in 9 cases of fuselage break.

For 15 accidents in which the gear was known to be retracting or in stowed position, there are only 5 cases where having gear extended may have prevented the crash. These cases mostly involve extensive slide-out, but occurred during aborted takeoffs or flight activities for which the gear is normally retracted.

From the above discussion it may be concluded that development of gear more tolerant to conditions that cause separation would result in some increase in crashworthiness. Further, when separation does occur, the wing box should not tear open.

CABIN INTERIORS

Cabin interiors are cited in approximately one-third of the accidents in the data base. Cabin interior equipment includes overhead storage compartments, ceiling panels and lights, sidewalls, class partitions, galleys, and closets. Comparing cabin interior citations with the accident severity category (see table 4.4) some peculiarities may be observed. For instance, it might be expected that accidents in categories 3 to 6 would have a higher percentage of citations than is actually reported. This is particularly applicable to accident categories 5 and 6.

The disparity might be attributed to the expectations of the investigator. If the damage is such that overhead compartments, ceiling panels, etc. might be expected to separate and clutter the scene, the occurrence may not be reported. Further, if the devastation is such that participation of the cabin interiors as compared to other factors might be considered secondary in survivability of the occupant, the participation may be unreported. While the absolute level of participation may equal that of a less severe accident, the relative contribution may be significantly less. Finally, post-impact fire may destroy visual evidence and survivors may not report conditions.

Consequently, the 45 accidents where citations have been made should serve as an indication of possible crash behavior of interior equipment. The 23 accidents where probable participation has been assessed may not include all incidents. In some accidents where at least one part of the interior participated, other parts have been deemed probable.
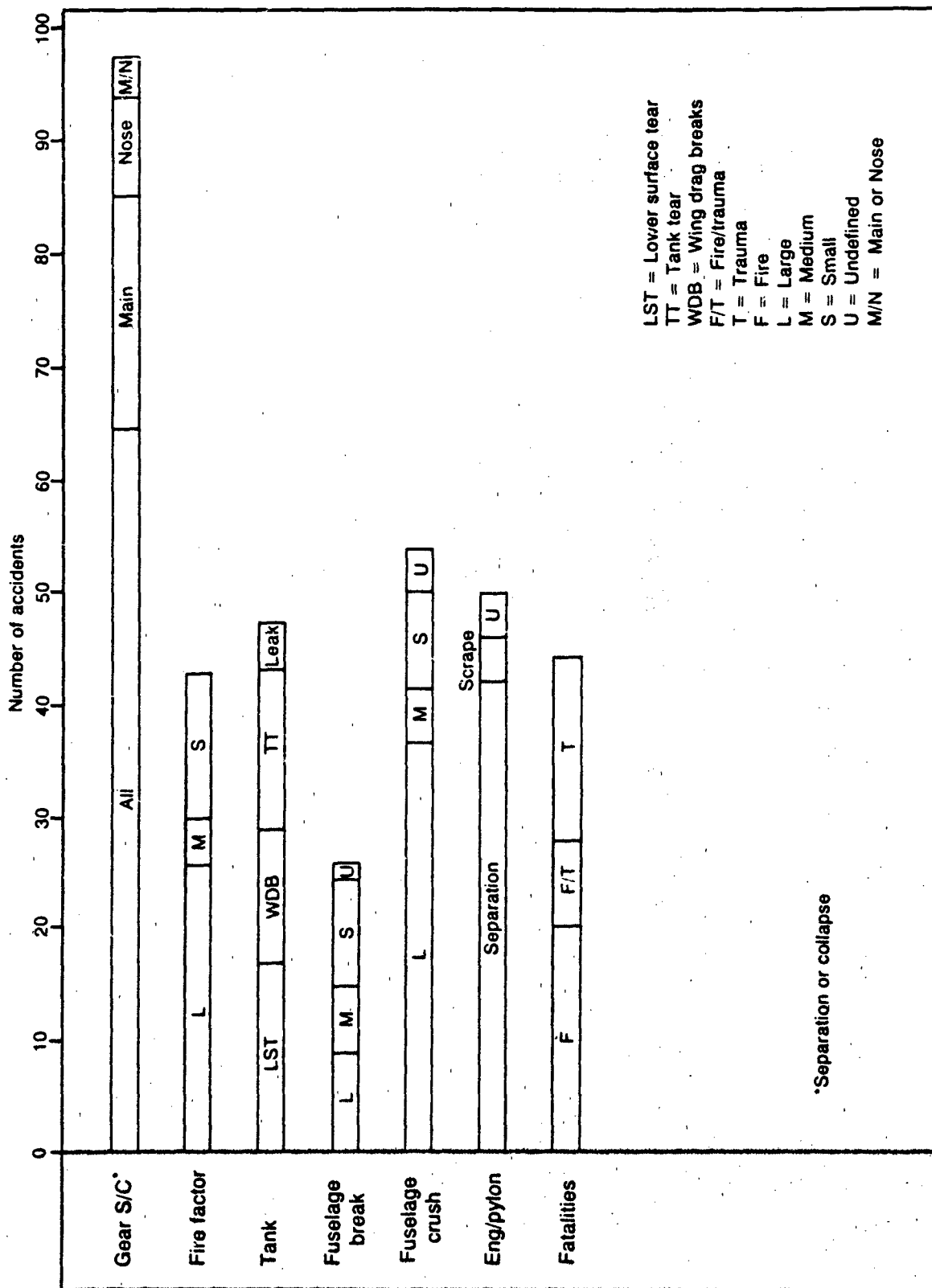
Figure 4.9– Gear Separation

Overhead storage compartments have been assessed with regard to separation, contents spillage, evacuation blockage, and injury to occupants. Ceiling panels, sidewall liners, and class partitions have been assessed for separation. This separation usually has some effect on egress. Galleys have been assessed for contents spillage as well as egress blockage. These units are of particular concern since they affect availability of the service doors as an egress route. These assessments are shown in figure 4.10. Cabin interiors have been a major factor in evacuation in 12 known accidents and probably in 14 accidents. Overhead storage has caused injuries in five known accidents and probably caused injury in three additional accidents.

Figure 4.11 shows interaction between other structural systems and the cabin interior system. Crush of the lower fuselage is deemed to have occurred in 52 of the 68 accidents. Fuselage breaks are deemed to have occurred in 32 of the 68 accidents. Landing gear separation or collapse occurred in 48 accidents and the gear was retracted in 6 other cases. Floor distortion is deemed to have occurred in 26 accidents. All of these interactions participate in severely loading the structural supports for the cabin interior equipment. Fire was present in 41 of the accidents.

FUSELAGE BREAK ACCIDENTS (Excluding Fuselage Lower Surface Rupture)

Of the 153 impact survivable accidents used in this Survivability Study, 64 are known to have experienced one or more breaks in the fuselage and 7 others probably also had breaks. Forty-six of the 64 were fatal accidents. Available data indicates that 39.5% of the persons onboard in the 64 accidents were fatalities. The other 82 accidents in this study did not experience fuselage breaks and 27 of these were fatal accidents of the persons onboard in the 82 accidents, 20.6% were fatalities. These data are plotted as follows:

Fatalities
Percent of total onboard

| | 0 | 10 | 20 | 30 | 40 | 50 | 60 |

Fuselage break accidents

Total 64

Fatal 46

No fuselage break accidents

Total 82

Fatal 27
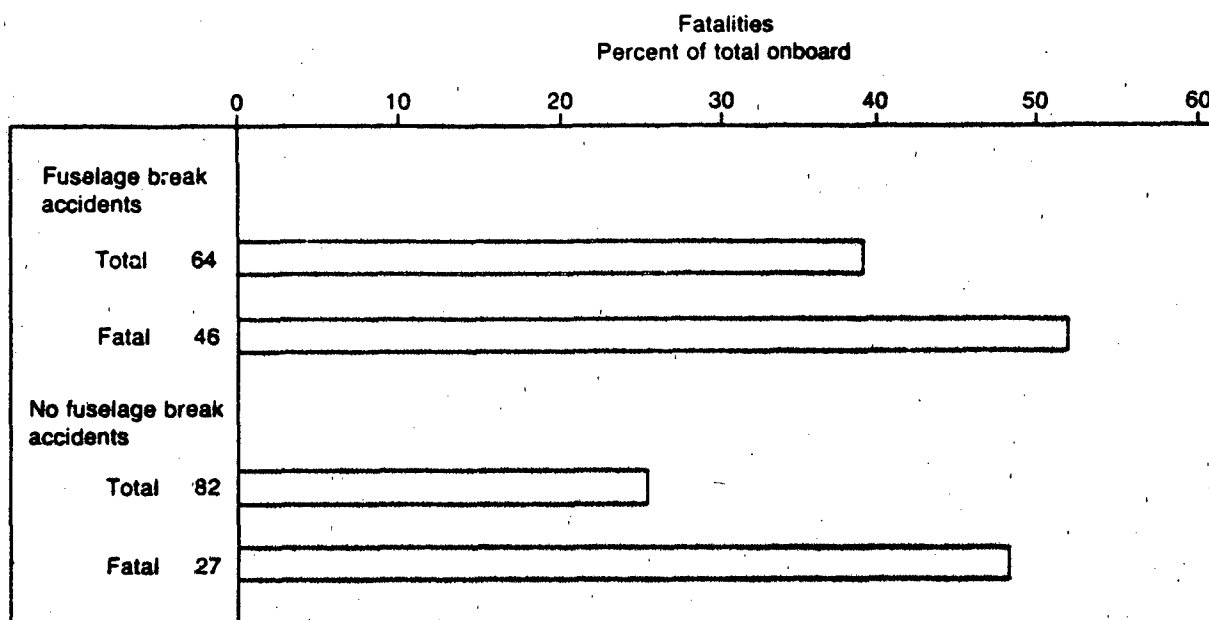
Of the 64 accidents experiencing fuselage breaks, 6 involved the aircraft touching down in deep water and 58 involved the aircraft touching down (impacting) on ground or in swampy areas with shallow water. Data on these accidents are plotted as follows:
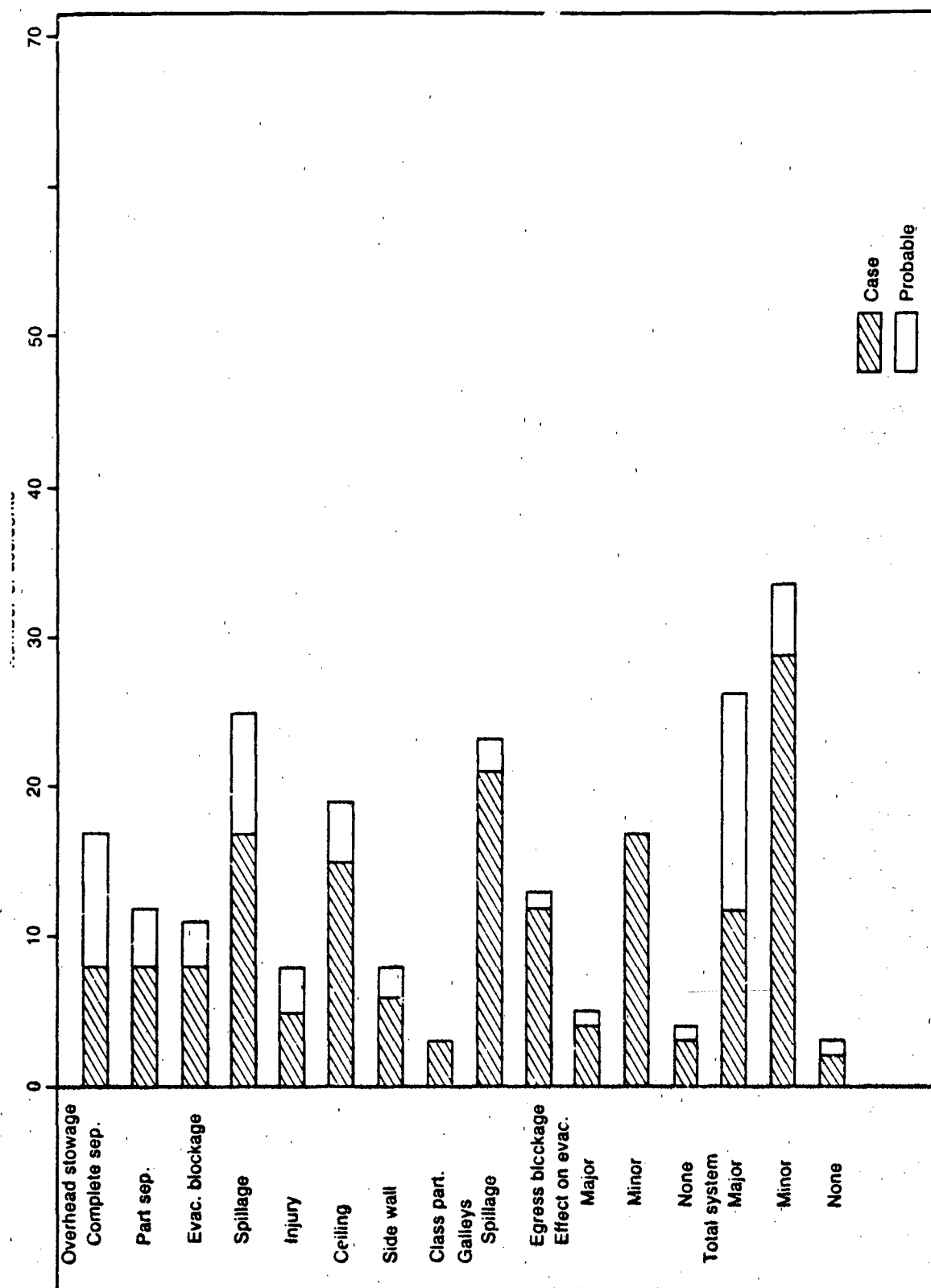
Figure 4.10–Assessment of Overhead Storage, Ceiling Panels and Sidewall Panels
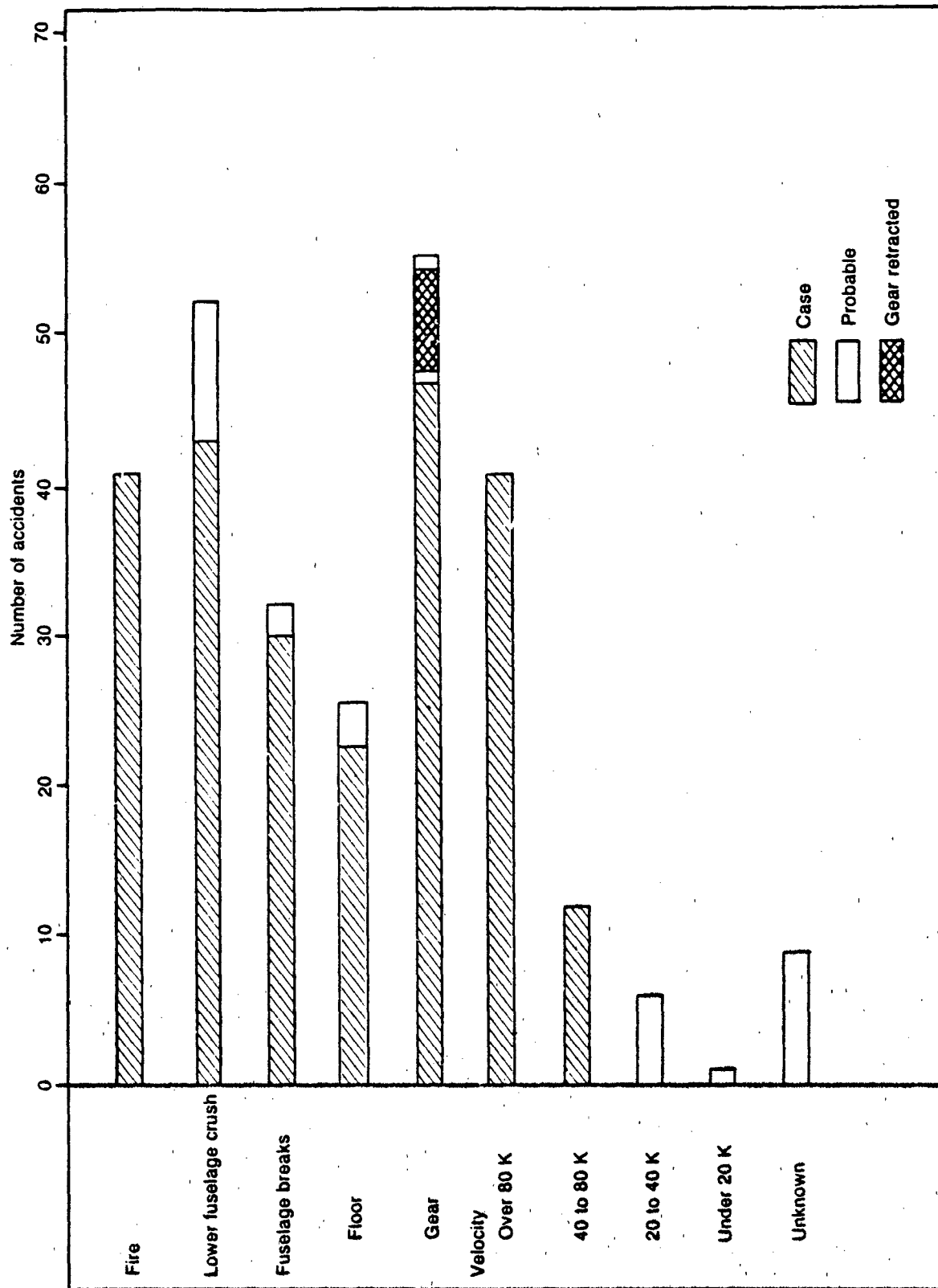
Figure 4.11-Interaction Between Cabin and Other Structural Systems

```
         0        10        20        30        40        50        60
         |         |         |         |         |         |         |
```

Accidents in
deep water

Total   06

Fatal   06

Accidents on
ground

Total   58

Fatal   39
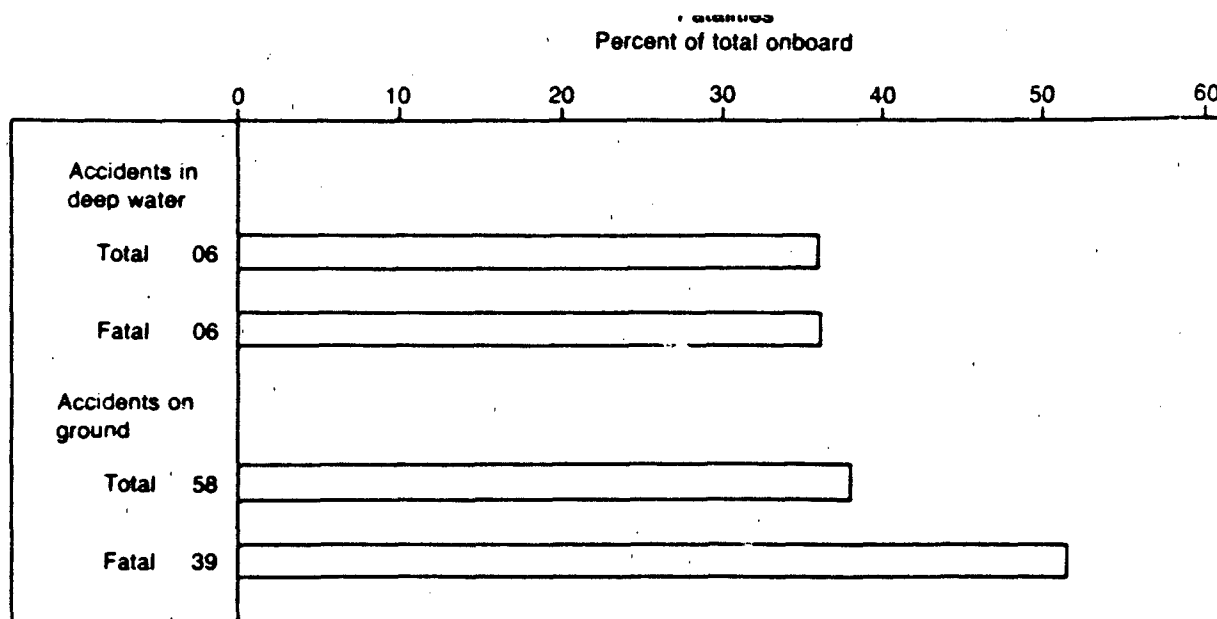
Deep Water Entry Accidents

Six water entry accidents in which the fuselage broke into several pieces had fatalities (36.8% of those persons onboard were fatalities). In five of these accidents one section of the fuselage sank rapidly — some of the passengers and crew probably were ejected or fell into the sea without benefit of survival gear and others were trapped inside. The other sections floated briefly, allowing evacuations into rafts or floating slides. In other accidents the fuselage sections floated briefly, however 84% of those onboard drowned. Survivor reports indicated that in at least two accidents, interior and carry-on debris blocked evacuation routes and in two other accidents some exit doors were jammed. In another, the passenger compartment floor was displaced upward restricting evacuation.

There were also four accidents involving deep water entry in which the fuselage did not break, and 25.9% of those onboard were fatalities, most believed due to drowning.

However, in these accidents the aircraft floated at least 5 minutes and in most cases 10 to 20 minutes, thus allowing adequate time to escape. In three of the four accidents it was established that the onboard rafts and float slides were not used.

It can therefore be concluded that in deep water entry accidents in which the fuselage does not break, the survivor rate should be very high with proper crew response/actions using available equipment. Designing the fuselage to resist breaks or separations is desirable.

Ground Slide Accidents

Fifty-eight ground slide accidents experienced fuselage breaks due to main landing gear separation/collapse, excessively hard touchdown or hard flat/impact after takeoff, touchdown in areas of trees/building/objects or on rocky/rough terrain, or combinations of these conditions.

Gear Separations — 8.6%— In 5 accidents, landing gear collapse or separation is believed to have contributed to the fuselage breaking; that is, if gear had not failed the fuselage may not have broken.

72

These are generally cases of the aircraft veering off the runway onto reasonably smooth terrain or touching down on smooth terrain and then having one or both main landing gear separate due to impact with a slightly raised road or small ditch. These five accidents resulted in a clean break in the fuselage, wide enough for a person to be ejected, fall out, or step out. Approximately 11% of those onboard in the five accidents were fatalities. Fatalities occurred in three of these accidents and in each case a severe fuel fire developed. The other two had no fatalities and no fire.

Hard Touchdown — 8.6%— In five accidents, the aircraft experienced a hard touchdown in a landing attitude or stalled after takeoff resulting in level attitude impact with sufficient vertical load to cause the fuselage to break. Two of these accidents resulted in slight breaks/fractures that would not result in ejection of persons or provide a means of exit/evacuation; there were no fatalities and no severe fuel fire. The other three accidents resulted in fuselage breaks that were wide enough to allow ejection of persons or provide a means of crawling, stepping out during evacuation. Of the 45 persons onboard in three accidents 64% were fatalities; all three experienced severe fuel fires. There is a high probability of flame and smoke entering open ends of the fuselage sections.

Aircraft forward speed was believed to be reasonably low in three of the accidents since the aircraft were in a stalled condition at impact. In the other two accidents the aircraft touched down slightly short of the runway at a high rate of descent, with forward speed probably 10 to 15 knots less than planned.

Rough Ground — 8.2% — In 48 accidents, the aircraft experienced fuselage breaks after touching down on terrain where impact occurred with trees, poles, gulleys, ditches, embankments, raised roads, etc. or where impact occurred with one wing low on a reasonably smooth surface (on airport, marsh, dry lakebed, etc).

Data on these accidents are tabulated in the following chart.

Onboard fatalities
Severe Fuel Fire

Percent of total

25   50   75

Slight break

Average speed
– 57k

Clean break

Average speed
– 83k

Fuselage torn

Average speed
– 136k

73
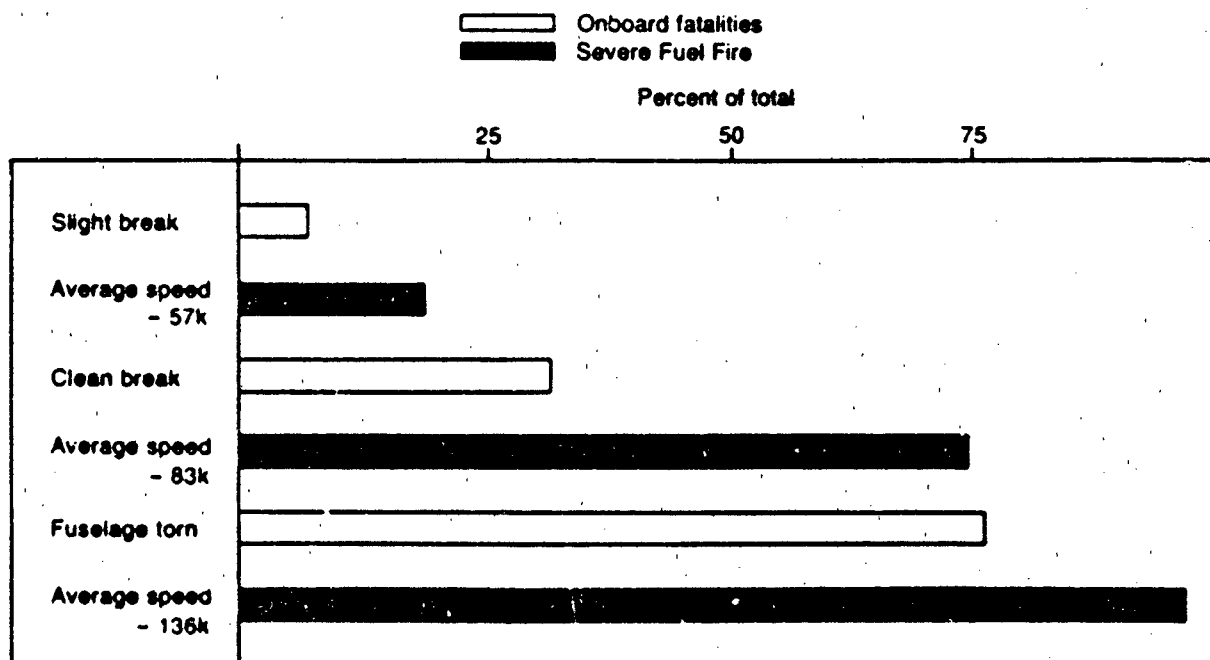
1. Twelve accidents involved a slight break(s) or fracture in which fuselage sections did not separate far enough for a person to be ejected or for a person to crawl or step out during evacuation (class 1). These accidents generally occur on or near the airport and as a result of landing overruns, takeoff abort, or veering off the runway. Impact which caused the fuselage break usually occurred after considerable brake action plus decelerations off the runway. Only two of the accidents (16.6%) involved a severe fuel fire, and only 6.3% of the persons onboard in these 12 accidents were fatalities.

2. Twenty accidents involved a clean, wide break in which the fuselage section remained basically intact but separated far enough for a person to be ejected or to crawl/step out (class 2). About 75% of these accidents involved severe fuel fires and 29.4% of the persons onboard in these 20 accidents were fatalities. Approximately half of these accidents involved aircraft speed at or near impact of 100 knots or more.

3. Sixteen accidents involved considerable destruction of the fuselage sections and in most cases the sections slid or traveled many feet after separation (class 3). During this movement persons were often thrown/ejected from the remains of the fuselage section. In some cases ejected persons were killed from trauma, and in other cases the ejected persons survived because they were thrown out of a fire or burn area. About 93.8% of these accidents involved severe fuel fir nd 77.8% of those onboard in these 16 accidents were fatalities. In most cases the aircra speed at impact was well over 100 knots — two of these had an impact speed of 188 and 271 knots, yet some persons survived. Many accidents in this group can be considered to be only marginally survivable.

It can be concluded that the probability of fatalities in accidents resulting in fuselage breaks during ground slides is closely related to aircraft speed at the time of impact that breaks the fuselage. The group of accidents resulting in only slight breaks (class 1) had an average aircraft impact speed of 57 knots and 6.3% of those on board were fataliti . The group resulting in a clean (but open) break (class 2) had an average speed of 83 knots and 29.4% were fatalities. The group resulting in a torn fuselage (class 3) had an average speed of 136 knots and 77.8% were fatalities. The greater the speed, the greater the fuselage damage and the greater probability of fuel tank rupture causing severe fire. However, even in the worst cases, some persons onboard survived. Design changes that would result in a stronger fuselage that is more resistant to fragmentations should provide a substantial increase in survivability for those onboard.

FUSELAGE LOWER SURFACE RUPTURE (Excluding Fuselage Break Accidents)

Of the 153 impact survivable accidents in this study, 57 aircraft are known to have experienced considerable damage to the lower fuselage and little or no damage to the upper fuselage (above the floor line). Seventeen of these 57 were fatal accidents, with 17.5% of the persons onboard being fatalities. In addition to the accidents noted above, there are seven accidents that probably experienced fuselage lower surface damage; three of these were fatal accidents with 45.8% of the persons onboard being fatalities.

Lower surface damage accidents are divided into three groups for study purposes: extensive rupture, minor or moderate damage, and those involving water entry. Statistical data on these accidents are tabulated on figure 4.12. The three groups are discussed as follows:

1. Twenty-eight accidents experienced extensive damage and rupture of the fuselage lower surface. Eleven of these were fatal accidents with 27.7% of the total onboard the 28 accidents

Figure 4.12–Lower Fuselage Surface Rupture (Exclude Fuselage Breaks)

	Total on board	Total fatalities	% fatalities	Fire no of accidents			Landing gear coll sep. no of accidents					Type of accident no of accidents					
				Severe	Moderate or minor	None	MLG one or both	Nose gear	MLG (one or nose gr both)	All gear up stowed	Nose gr coll into fwd body	Touch down short	Hard touch down	Veered off runway	Misaligned touch down on airport	Slide on runway	Over run TO or landing
Extensive Rupture 25 Total (9 Fatal)	2349	658	28.0	15 (9)	5 (0)	5 (0)	9		14	2		11		4	1		8
5 Probable (3 Fatal)	269	160	59.5	3 (3)	0	2 (0)	1		4					3			2
Minor Moderate Rupture 25 Total (3 Fatal)	1535	23	1.5	10 (2)	6 (1)	9 (0)	8	3	5	3	6	4	3	10	1	1	5
2 Probable (0 Fatal)	80	0	0.0	1 (0)	0	1 (0)	2										2
Water Entry Rupture 4 Total (3 Fatal)	297	41	13.8	0	0	4						2					2
Deep Water 3 Total (3 Fatal)	226	41	18.1	0	0	3											1
Shallow Water 1 Total	71	0	0.0	0	0	1	Resting on gear										
Total 54 Total (15 Fatal)	4181	722	17.3	25	11	18											
7 Probable (3 Fatal)	349	160	45.8	4	0	3											

being fatalities. A severe fire occurred in 15 of the accidents and 9 of these were the fatal accidents. Six other accidents involved a minor or moderate fire with no fatalities.

2. Twenty-five accidents experienced moderate or minor damage of the fuselage lower surface. Of these only three were fatal accidents, with 1.5% of those onboard the 25 accidents being fatalities.

   Six of these accidents involved a severe fuel fire, four involved a moderate or minor fire, and six had no fire reported. Of the three fatal accidents, two had severe fires and one a moderate fire.

   Six accidents involved nose gear collapsing aft into the lower fuselage. One resulted in a severe fire (friction ignited) which destroyed the aircraft and one resulted in a moderate fire (friction ignited) which resulted in substantial damage. In another case of friction fire, the aft fuselage broke and was dragged on the runway.

   In design, the prevention of friction fires is treated by separation of flammable materials from the proximity of friction sparks or heated structure. In operation, rapid action by the airport fire fighting team has reduced the effect of the friction fire.

3. Four accidents involved water entry; that is, touchdown in deep water or rolling into deep water at high speed such that the lower surface of the fuselage was torn or ruptured but the fuselage did not break. Three of these four accidents resulted in extensive lower surface damage and the aircraft sank rapidly. All three were fatal accidents with 18.1% of persons onboard being fatalities. One accident resulted in moderate damage to the lower surface as the aircraft rolled into water and came to rest on its gear with the water level at or slightly above the cabin floor. There were no fatalities. These accidents were also discussed before, in this section, under heading "Deep Water Entry Accidents."

Lower fuselage tear or rupture generally occur when landing gear fails to support the aircraft. Thus, scrubbing on rough surfaces (sometimes even on the runway) rips open the thin skins and body frames. At the same time, wing box fuel tanks are also subject to rupture and fuel spillage. In 37 of 53 ground slide accidents the wing box was probably ruptured and, of these, fire occurred in 32 — 25 were severe fires and 12 were minor or moderate fires.

It can be concluded that the probability of fatalities in accidents resulting in lower fuselage tear or rupture during ground slide is closely related to the occurrence of severe fuel fire. Flame and smoke from fuel burning on the ground below and around the fuselage have, in many cases, rapidly entered the passenger area via openings in the lower fuselage. If openings had not been present, the precious minute or two required for skin burn-through would probably be adequate for evacuating most or all persons via escape routes away from burn areas. Of the 12 fatal accidents during ground slide, 11 had severe fire and one had a moderate fire.

FUSELAGE FLOOR DISPLACEMENT

Displacement and rupture of the passenger floor has resulted in passenger and crew injuries, and has restricted movement of survivors to exits. In some cases the upward movement of the floor has resulted in the jamming of doors or door frames and in other cases doors could not be opened due to floor debris blocking the door. Generally, floor surface displacement is a result of the structural floor beams being torn, ruptured, and displaced upwards by the impact forces of cargo, cargo containers, separated landing gear or ground objects. The exception to this is floor displacement by the hydraulic action of water when the aircraft touches down in water or rolls into water at high speed — in these cases the floor beam may not be displaced upward.

Of the 153 accidents in this study, 36 are known or reported to have experienced passenger or crew area floor displacement or rupture and probably in 4 other accidents. Statistical data on these occurrences are tabulated in figure 4.13. For study purposes, these 36 accidents are divided into three groups: 15 that did not involve a fuselage break, 17 that did involve a fuselage break, and 4 that involved the aircraft touching down or overrunning into water. These groups are discussed as follows:

1. Of the 15 accidents which did not have fuselage breaks, 8 involved displacement upwards of the cabin floor as a result of the nose gear folding/collapsing aft into the lower forward fuselage cargo compartment or electronic compartment. Displaced cargo or electronic equipment forced the floor up and probably tore or bent the floor beam. In four of these accidents the cockpit door was jammed, and in two the entrance door was jammed or blocked. None of these were fatal accidents, however, one resulted in a friction-ignited fire at the nose gear tires which spread and destroyed the aircraft.

    Seven other accidents involved a ground slide in which the fuselage lower surface was torn or crushed upward such that floor and floor beams were displaced upwards in localized areas. In one of these a main landing gear assembly rolled/tumbled under the fuselage and caused much of the damage. In three accidents, an entrance door was jammed or blocked by the floor. Passenger seat elevations occurred in seven accidents which contributed to passenger injuries. In three accidents passenger seat separations occurred. Accident reports in these cases did not mention seat separation or floor displacement as interferring with passenger egress.

2. Seventeen accidents which had fuselage breaks also had areas where the floor was displaced upwards. These accidents tend to be more severe than those without fuselage breaks. If fuselage separation is complete and wide enough for human and seat ejection, the impact of passenger floor elevation or rupture is probably slightly minimized. In 13 accidents passenger seat separation was reported, in 9 accidents seat elevation was reported, but in only 4 accidents was passenger egress reported to have been impeded. It is not known how much impact the elevated or broken floor had on passenger egress. Passenger entry door jam was reported in five accidents and crew door jam in two accidents. Cause of these door jams in most cases could not be established with any certainty but was probably due to either floor elevation/rupture or due to fuselage break if the break was adjacent to the door.

3. Crew/passenger floor elevation and rupture occurred in four accidents which involved the aircraft touching down in deep water or rolling into water at high speed. In these cases the lower fuselage surface was torn open and the lower (cargo) area filled with water. Hydraulic action/pressure forced the floor panel upward, causing seat separation in two accidents and seat elevation in three accidents. Exit doors were found to be blocked in two accidents.

In one accident, the forward closet dislodged. It shifted forward in such a way that the forward entrance door was partially blocked and delayed opening of the door. Also a section of floor came up and provided an opening in which two of the crew fell into the lower forward compartment.

In another accident, nose gear separated and tumbled aft, forcing up and rupturing the lower fuselage. Floor beams and floor panels were elevated causing passenger seats to tilt backwards and block emergency exits on both sides of the fuselage.

Available accident data provides evidence that displacement, elevation, or dislodging of the passenger/cockpit floor system in localized areas has resulted in passenger and crew injuries and

Number of accidents

	Total on board	Total fatalities	% fatalities	Location of displacement Fwd	Mid	Aft	Separation	Seat elevation	Exit door jam/ blocked	Crew door jam/ blocked	Egress inter- ference	Nose gear folded aft	MLG tumb. under body	Grd. slide	Fire Sev- ere	Mod- erate
Floor displace. (Excluding fuselage break) Total – 15 (2 Fatal)	1126	18	1.6	12	1		3	7	5	4		8	1	8	4	4
Probable – 1 (1 Fatal)	63	6	9.5			1			1		1					
Floor displace. (Involving fuselage break) Total – 17 (11 Fatal)	1477	368	24.9	10	7	9	13	9	5	2	4	1		14	7	3
Probable – 3	339	132	38.9	2	2	2	1	2	1						2	
Floor displace. Due to deep water entry Total – 4	254	35	13.8	3	1	1	2	3	2		1	1				

Figure 4.13–Passenger/Crew Compartment Floor Displacement

has, in varying degrees, interferred with or delayed the evacuation of passenger and crew. However, accident reports generally provide very little detailed information on this type of damage unless it is related to the cause of the accident. Studies of these areas must rely on brief statements and accident photographs which seldom "zero in" on the desired areas. It is concluded from reviews of available data that a floor system more resistant to tear/rupture/separation, though still flexible, may reduce some of the debris and factors which are believed to impede evacuation of the aircraft.

ENGINE/PYLON SEPARATION OR COLLAPSE

Separation of an engine from the pylon or separation of the pylon from the wing or body often occurs in accidents involving touchdown, short/hard touchdown, overruns, or veering off the runway. When one or both main landing gear collapse during these types of occurrences, the probability of engine pod damage or separation is increased. Generally, loss of the engine (forward or reverse thrust) is of minor significance but rupturing of the engine fuel feed line (releasing fuel) and tearing of electrical leads (causing arcing) can be a hazard because of the potential for a fire occurring at the fuel feed line break point. The significance of this pylon break fire hazard increases if the wing fuel tanks are ruptured and large quantities of fuel are released on the ground. It is believed that the engine and the pylon break fires have been the ignition source for many of the fuel tank fires. Accident reports seldom confirm or deny this, since it is not generally possible to establish from evidence at the accident site what actually provided the ignition source. In some occurrences, friction sparks from wing or fuselage sliding on terrain may have caused ignition of released tank fuel only seconds or microseconds before an engine pylon fire occurred. There is no known way to establish the actual sequence of the events. However, from a review of accident data, there appears to be a relationship between wing tank ruptures, severe fuel fires, and pylon break fires that indicates pylon break fires probably provided the source of ignition for released fuel in many accidents.

Of the 153 accidents in this crashworthiness study, 94 involved aircraft with engines on wing pods and 59 involved aircraft with engine pods on the aft fuselage. These two groups of aircraft are reviewed separately.

Wing Pod Engined Aircraft Accidents

Of the 94 accidents (including known and probable occurences) involving wing pod engined aircraft, 67 (71%) involved rupturing of the wing box fuel tank and 68 (72%) involved collapse or separation of the engine pylon to the extent that the engine fuel feed line was torn or ruptured. The occurrence of these two types of damage are shown in figure 4.14.

Fuel fires originating at the fracture of the engine fuel feed line in the pylon are reported to have occurred in 12 accidents and probably occurred in 33 accidents. No fires were reported at this fracture point in 23 accidents.

The proximity of the wing pod engine to the wing box fuel tanks has resulted in correlations between engine separation, fuel tank rupture, and a severe fuel fire. Approximately 71% of the accidents involved rupture of the fuel tank and releasing fuel on the ground and, of these, 91% were considered large fuel spills such that the spill area probably was near or adjacent to the engine pylon location. The study shows that 82% of the large fuel spills resulted in severe fires and, in 78% of these, a ruptured engine pylon fuel line fire probably also occurred.

In numerous accidents, separated engine pods have rolled or tumbled under the wing or fuselage as the aircraft slides to a stop. However, accident reports seldom indicate that the pod ruptured the wing box fuel tank in this movement. In most cases, investigators are probably unable to determine what objects actually caused tank rupture.
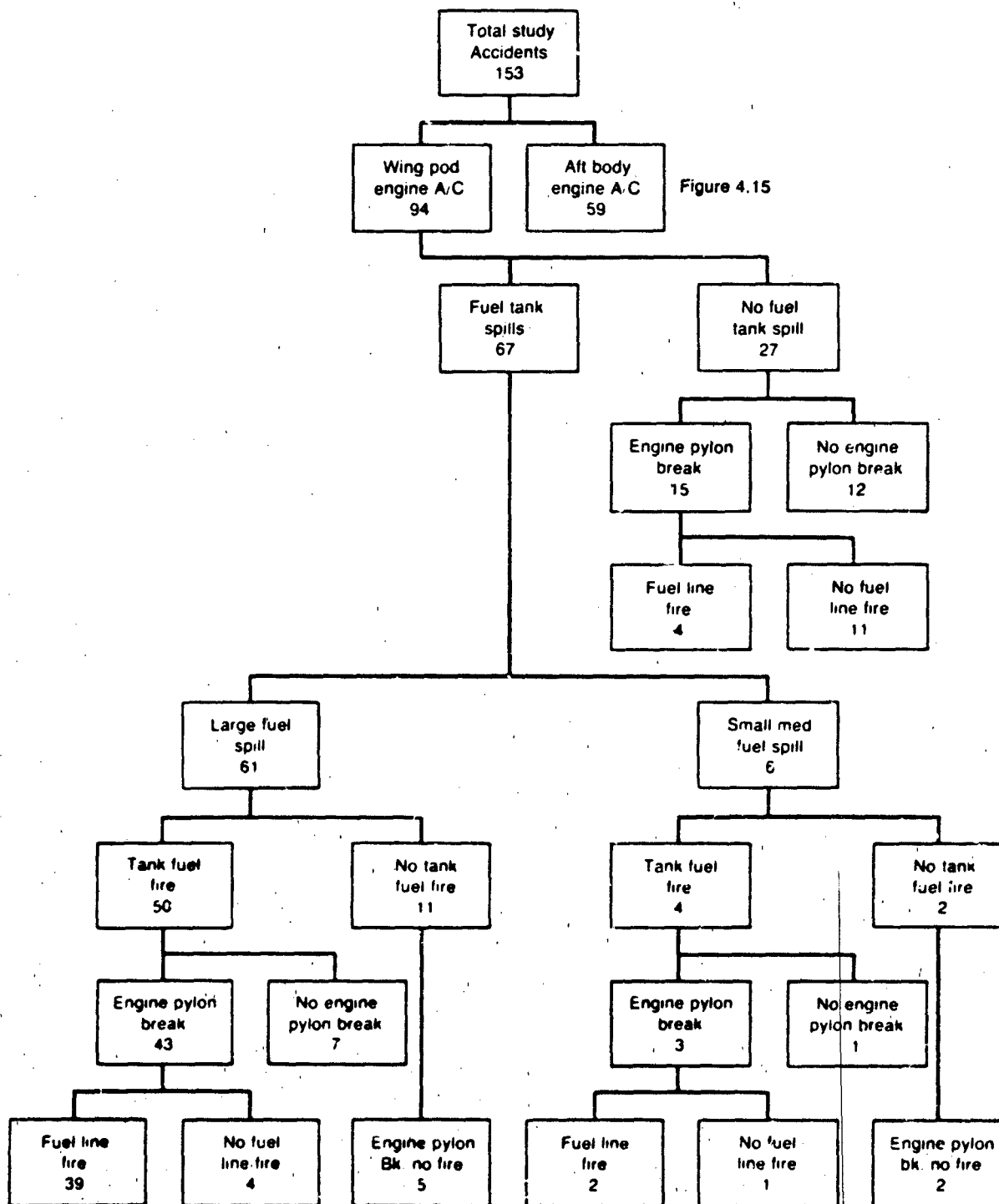
Figure 4.14-Engine/Pylon Separation/Collapse and Fuel Tank Rupture, Wing Pod Engined Aircraft

Aft Body Engined Aircraft Accidents

Of the 59 accidents involving aft body engined aircraft, 38 (64%) involved rupturing of the wing box fuel tanks and 21 (36%) involved collapse or separation of the engine pylon to the extent that the engine fuel feed line was torn or ruptured. The occurrences of these two types of damage are shown in figure 4.15. Of the 21 occurrences involving engine/pylon collapse or separation, 7 resulted from a very hard touchdown, 7 due to impact with ground objects, and 7 due to high vertical loads as the aircraft slid over rough ground or impacted water. No engine pod separations were known to be caused by pod ground contact during aircraft slide on the lower fuselage.

Fuel fires originating at the fracture of the engine fuel feed line in the pylon are reported to have occurred in two accidents and probably occurred in five accidents. Reports indicate that no fire occurred at this fracture point in 14 accidents.

Severe wing tank fuel fires occurred in 26 accidents but, of these, engine/strut fuel line fires were reported in 1 and probably occurred in 5. This indicates that wing tank fuel, in 77% of these cases, was ignited by something other than by an engine fuel feed line fire. In the other 23% (six cases) the reports do not indicate or show evidence that the engine fuel feed line fire provided the ignition source for the wing tank fuel fire. In most accidents, the investigators are probably unable to determine the actual source of the spilled tank fuel ignition.

Engine Fuel Feed Line Fire Hazards

In the 153 accidents used in this study, loss or collapse of an engine or pylon generally creates a potential hazard only if a fire occurs at the point of fuel feed line rupture and, if in flight, the fire is sustained for possibly 30 seconds or more. In wing pod mounted engine aircraft, the hazard is ignition of spilled wing tank fuel or overheating of wing fuel tanks to the point of explosions or skin burn-through. If tank fuel is not ignited, the engine strut fire itself generally has little impact on passenger evacuation or survivability.

In aft body engined aircraft, the hazard is burn-through of the aft body skins and a fuel line fire burning vital controls and systems within the aft body. These fires, being remote from the wing box fuel tanks, are a potential source of ignition of tank fuel only if the tank fuel is spilled in the area under or around the aft engines.

Conclusions:

1. Engine fuel line fires caused by engine separation or collapse are a hazard of underdetermined dimensions, particularly in wing pod engined aircraft accidents. The source of ignition of spilled tank fuel is seldom reported and probably, in most cases, cannot be actually determined. Nevertheless, research should be accomplished in the area of minimizing the flow or volume of fuel released from a fractured engine fuel feed line and eliminating the sources of ignition of this fuel.

2. Wing box fuel tanks have, on rare occasions, been torn open when engine pylon separates from wing structure. Study should be accomplished to develop structure fuse points to assure a clean strut separation. This could include clean fuel line separations and electrical lead separations without arcing.

3. Engine pylon separation or collapse often follows separation or collapse of one or more main landing gear. It is not possible to determine from accident reports how many engine pylons would not have separated or collapsed if the main landing gear had not collapsed. It appears,
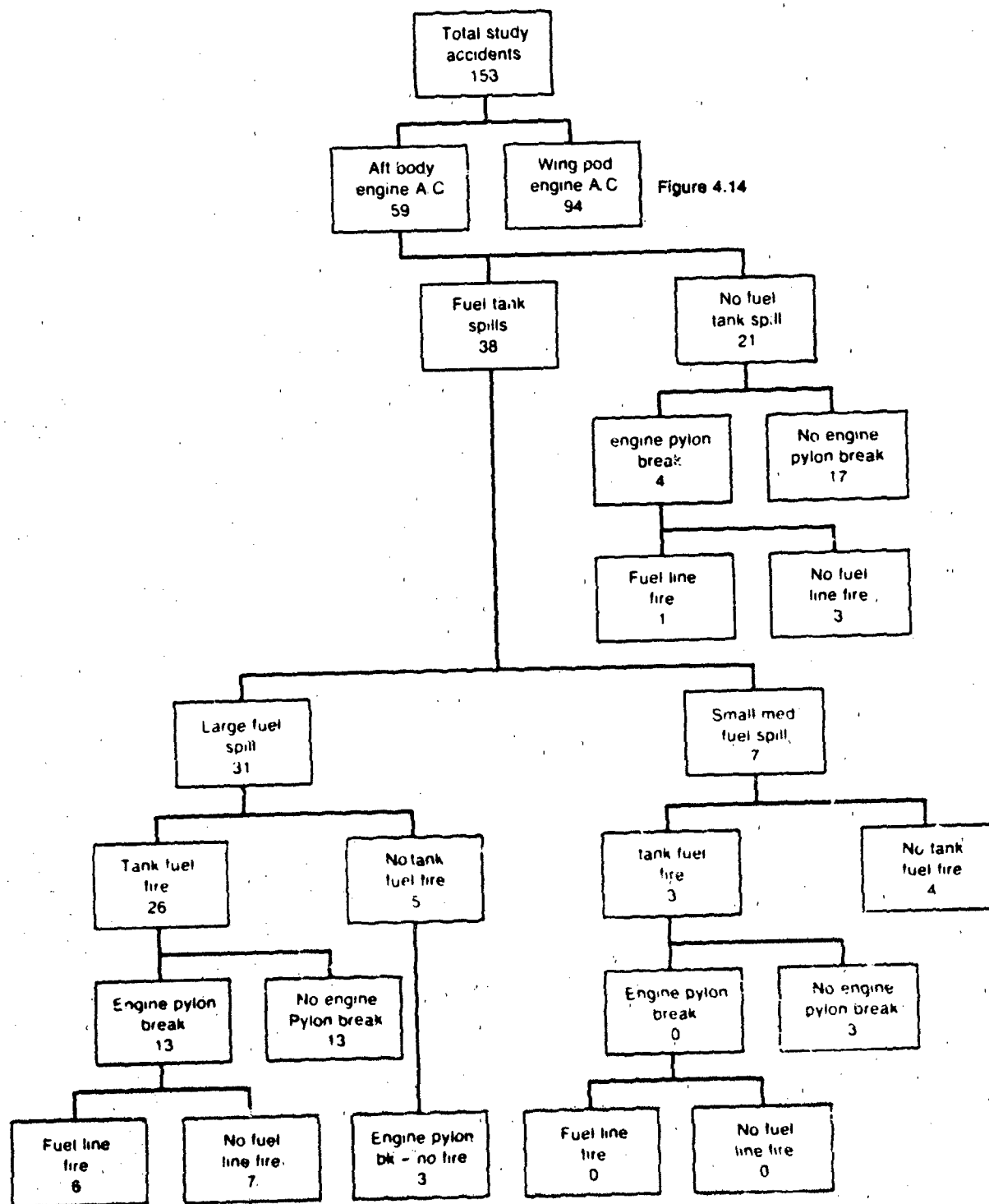
Figure 4.15-Engine/Pylon Separation/Collapse and Fuel Tank ... oture, Aft Body Engined Aircraft

however, to be of a sufficient number to justify research in landing gear design philosophy and development of landing gear is more tolerant of travel over rough, soft terrain off the runway.

CABIN DOOR OR EXIT JAMMING OR BLOCKAGE

Of the 153 impact survivable accidents studied, reports for only 47 accidents cited occurrences of entry door, galley door, cockpit door, or emergency exits jamming or being blocked by cabin equipment, debris, or outside objects. It is believed that door or exit related evacuation problems also occurred in many other accidents.

Fuselage breaks often provide a handy and expeditious means for some of the passengers and crew to evacuate the aircraft. In 10 of the 47 accidents, where door/exit problems were cited, the reports also indicated that some passengers and crew departed via breaks and holes in the fuselage. In most cases these people could have also departed through available doors or exits. However, in a few cases the fuselage break was probably the only means of escape.

In many accidents which involved severe fuel fires, some doors or exits could have been readily opened but were not used because of fire in that particular area outside the fuselage.

Available factual data relating to the 47 accidents citing door/exit problems are tabulated in figure 4.16. These data indicate that most occurrences (57%) involve doors at the front of the fuselage and only 16% at mid-body and 27% at the aft fuselage. This ratio is expected since in ground slide accidents the forward fuselage is the first to impact objects such as buildings, trees, poles, etc. These data also indicate that forward fuselage doors involved jamming in 64% of the cases and blockage in 36% of the cases. Doors in the aft fuselage had approximately the same ratio. Mid-body exits, however, had this ratio reversed with blockage being 64% of the cases and jamming only 36% of the cases. It is probable that wing box structure provides protection from jamming of the mid-body overwing exits.

Considering all doors/exits, jamming is reported in 59% of the cases and blockage in 41% of the cases.

Jamming is generally caused by door frame distortions, however, accident reports seldom provide much detail on how or what caused the problem. Floor-lift due to upward forces from the cargo area often cause total or partial jamming of doors. The same upward forces may also cause door frame distortion. In a few cases evacuation slides are involved in door jamming.

Blockage is generally caused by collapsing of overhead storage compartments and release of the contents. This debris usually results in complete inability to open the door or exit. Spillage of galley contents occurs frequently, which tends to cause a delay in opening the door. In a few cases displacement of a galley or coat storage compartment has caused door blockage, particularly at the forward fuselage locations.

The number of fatalities that were a direct result of door jamming or blockage can seldom be determined or even estimated from available data. Of the 47 accidents in which door/exit problems were cited, only 24 involved fatalites (2187 total onboard of which 753 or 34.4% were fatalities).

Of the 24 accidents with fatalities, 9 had 2 or more doors or exits jammed or blocked and 41.9% of those onboard were fatalities. In the other 15 accidents only 1 door or exit was jammed or blocked and 27.1% of those onboard were fatalities.

Figure 4.16-Door or Exit Jamming or Blockage

Occurrences cited in 47 accidents

Number of cited occurrences

Door - exit location	Door or exit position	Jamming cause				Blockage cause					Could not be opened			Delay in opening	
		Frame distortion	Floor lift	Latch mech.	Outside object	Galley debris	Interior & misc debris	Undefined	Evac. slide or life raft	People panic	No other exit avail. all fatals	Divert to other exits some fatals	Divert to other exits no fatals	Divert to other exits some fatals	Divert to other exits no fatals
Fwd (39) 47%	L. entry	10	4	1	2		2		2	1		5	7	6	4
	Galley	2	2	1		3	3		1	1		6	6		1
	Cockpit		3				1				1		3		
Mid body (11) 16%	Fwd wing														
	Over wing	3		1			6	1				4	3		4
	Aft wing														
Aft (18) 27%	L. entry	4	2				2					6	1		1
	Tail entry		2	1			1					1	1	1	1
	Galley		2			2	2					1	4		1
Total (68) 100%		19	15	4	2	5	17	1	3	2	1	23	25	7	12
		40 (59%)				28 (41%)					49 (72%)			19 (28%)	

From this study of door and exit problems during emergency evacuations, it can be concluded that survivability might be increased if floors and structure in the area of each entry and galley door be designed to eliminate jamming of doors, and if overhead storage compartments be designed to resist collapse and reduce door blockage.

WATER ENTRY

Accidents in which aircraft impact water or come to rest in deep water involve special hazards. In scenario type S13, 46.3% of the occupants drowned. There are 16 water accidents in the data base of which water was an important factor in 11 cases. These 11 cases are reviewed.

Water cases that are excluded are the 707 Oso accident, L-1011 Everglades accident, 727 Maderia accident, 727 Mexico City accident, and the 707 Rio de Janerio accident. These accidents resulted in trauma fatalities for the most part, and water was only incidental to the accident outcome.

Water entry accidents of concern appear to have some common factors. First, they usually occur at night. Second, there is usually a relatively rapid loss of flotation resulting in a portion or all of the aircraft sinking. Third, while there has been confusion, most occupants have been able to evacuate the aircraft. Finally, many of the drowning fatalities occur after the occupants have left the aircraft.

Assessment of the water entry accidents is shown in figure 4.17. The accidents are divided into two groups: high energy impact and slide/roll into the water. There are eight high energy accidents. For the Caravelle Maderia accident all that is known is that the aircraft touched down at sea, the fuselage is presumed to have broken, and the numbers of fatalities and injuries. Consequently, it is classified unknown. The DC-9 Palermo accident has a little data and is classified known, but is borderline. There are three cases where the aircraft rolled or slid into the water. For all of these accidents the fuselage experienced either lower surface crush or had one or more breaks.

In all the high energy impacts there was a loss of flotation attributed primarily to fuselage damage. While tank rupture resulted in some loss of buoyancy, the major effect of tank rupture was to expose occupants to fuel (chemical burns) and to make everything slippery.

The floor system was known to be disrupted in six of eight accidents. Disruption was due in part to the hydrodynamic forces of water entering the fuselage through the underside or through breaks in the fuselage.

A part of this disruption resulted in displacement and elevation of floor beams with subsequent separation of seats, and also contributed to problems in the evacuation of the aircraft. In addition, doors were jammed and debris from cabin interior systems was present. In the 727 Pensacola accident, water destroyed the lower fuselage, ruptured the body fuel lines, and separated an engine.

Accidents where aircraft skidded or rolled into water experienced similar damage as the high energy impact, but to a lesser degree. However, close proximity of land, substantially reduced drowning. The 15 drownings in the DC-8 Rio de Janerio accident were attributed to disorientation of the occupants after they evacuated the aircraft and to improper use of flotation devices.

After the DC-9 St. Croix accident, a special study (ref. 2) was made by the NTSB on water ditching. Here, even though it was known that ditching was inevitable, 23 occupants drowned. There were problems with life rafts, life vests, and seat belts. Other problems with this equipment were encountered in the DC-8 Los Angeles accident. It is felt that incidence of drowning could be substantially reduced by better location of life rafts. For instance, placement of rafts above the exits with external access might provide better accessibility.

Figure 4.17–Assessment of Water Entry Accidents
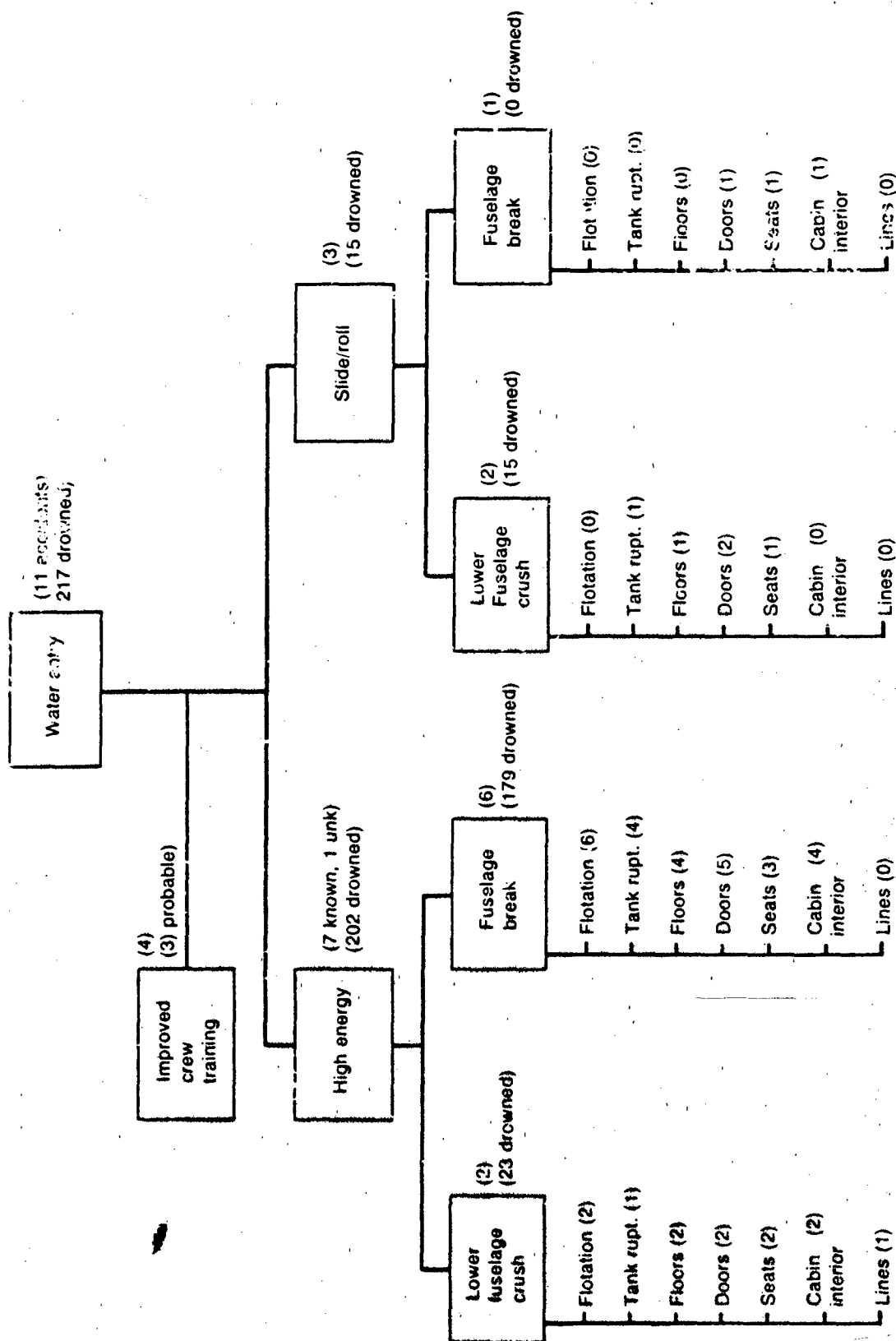
Improved crashworthiness might also be obtained by increasing the resistance of the fuselage to breaks and by increasing the resistance of the lower fuselage to water penetration.

ADVANCED MATERIALS

The application of advanced materials such as improved metal alloys and composites to structure that has a significant crash function is now considered. As seen from the above discussion, the conventional commercial aluminum jet transport aircraft designed to FAR 25 have demonstrated generally good structural crashworthy characteristics.

Consequently, those materials having fracture, impact and ductility properties similar to aluminum might be expected to be applicable on a direct substitution basis without affecting crashworthiness. Where the properties are dissimilar, such as for composites, questions are raised on how to maintain an adequate level of crashworthiness.

There is little data available on the crash behavior of composite structures. The U.S. Army has active programs directed towards the application of composites in helicopters as part of the ACAP and in sponsored research. In addition there are military research programs on ballistic damage to composite structure. Results of these programs will provide valuable information. While these results may not be directly applicable to the commercial jet transport, they may suggest approaches to research that may be fruitful.

Use and planned use of advanced composites in both military and commercial aircraft is in a rapidly expanding mode. Use of graphite/epoxy as a viable material for aerospace structures became a serious consideration in the mid-1960s with the development of Thornel graphite fibers by Union Carbide. Initially, use of the material was hampered by high cost and lack of technical data. Currently, both of these factors have been alleviated so that extensive use of the material is both feasible and advantageous. The impetus is the typically 20 to 30 percent reduction in structural weight that can be realized with accompanying increases in fuel economy or aircraft performance.

The application of composites on military aircraft is moving rapidly. The F-18 has wing skins and tail structures of graphite. The entire wing structure of the AV-8B Harrier is graphite, as are the forward fuselage and tail.

Planned use of graphite on future commercial transport aircraft is also aggressive. The Lear Fan aircraft is all composite structure and the Falcon 10 will have a graphite/epoxy wing box structure. The 757 and 767 aircraft will have control surfaces of graphite. These include the spoilers, ailerons, elevators, and rudders. Main landing gear doors will be a combination of graphite and Kevlar. There are also serious plans for other downstream uses of graphite on the 757. These include use of graphite for selected floor beams and for horizontal and vertical empennage inspar structures. Use of graphite for such parts as the main landing gear beam and flaps is also under study.

Graphite composites are used on the 757 and 767 aircraft for some components. Most applications are for secondary structure. Application in control surfaces follows Boeing's successful program with NASA, which tested and certified graphite/epoxy elevators for the 727. A similar program is underway for the 737 horizontal stabilizer. Graphite 737 stabilizer components have been successfully ground and flight tested and certification is expected in the near future.

In considering the various aircraft parts which will be fabricated from composites, it must be emphasized that these will be designed and tested to meet the requirements of FAR 25. As an example, floor beams will be analyzed and tested to ensure their being able to withstand the

stipulated 9 g seat forces. Similarly, crash load requirements will be included in the design of other components. The landing gear beam is designed so that it will break away in event of gear collapse so it will not puncture wing fuel cells.

The question becomes then, how will the structure react if the design crash loads are exceeded and importantly, in the event of a fire. Relative to this was a recent study to determine if graphite composites, if subjected to a catastrophic fire situation, might release filaments that would cause widespread electrical shorts and cause failure of proximity electrical equipment, for example failure of power substations. In this case, NASA concluded after extensive study, that risks involved with aerospace use of fiber carbon fibers were minimal. The potential loss rate was estimated at an insignificant $1000 per year (ref. 3).

Another important consideration is the mechanism for energy dissipation in a crash. This is to a great extent dependent on the structural configuration. Most effectively, dissipation is by deformation such as buckling or material elongation. The ability of structure to deform, however, depends strongly on the construction materials. Relative energy absorbing characteristics of materials are generally indicated by the area under their load deflection or stress/strain curve. Metals benefit from their relative high elongation capability or ductility. Fibers in composite structure by nature remain elastic to failure and have low elongation capability, thus their energy absorbing capability can be expected to be low. Differences between the two materials is demonstrated in figure 4.18.

Another meaningful comparison that can readily be made is elongation to failure. Graphite laminates typically fail at approximately 0.8 to 1.0 percent strain while 2024-T3 aluminum typically strains to 10 to 12 percent.

Some apparent ductility can be gained by stressing in shear or by testing axially with the fibers oriented off-axis, say at ±45° to the test axis. The shear case is demonstrated by a curve for a Kevlar fabric laminate in figure 4.19. Some gain in effective ductility may be obtained by off-axis reinforcement in multidirectional laminates, however, the gain is suspected to be small. Seemingly, when fibers inline with the load fail, load should be transferred to off-axis fibers with greater strain capability to absorb additional energy.

However, when the inline fibers fail, the effect, unlike a ductile case, is very dynamic and it is unlikely significant energy is absorbed. This instantaneous energy release is demonstrated by noting the three-piece failure of a graphite multidirectional laminate tension specimen in figure 4.20. In some cases, specimens may fail in 4 to 5 pieces as a result of initial failure induced shock waves.

A more effective method of improving energy absorbing characteristics is to add reinforcement fibers with higher strain capability. Examples are to use glass or Kevlar fibers. The effectivity of using hybrid techniques to improve impact properties has been demonstrated by use of an instrumented Charpy test. This is described in reference 4. While the conventional Charpy test is only concerned with total energy, the instrumented test differentiates between the initiation and propagation phase to give a ductility index. This is illustrated in figure 4.21.

The improvement in energy absorption characteristics of the graphite by two levels of Kevlar fiber additions is indicated by the total energy and ductility index figures in table 4.7. The improvement is significant.

Other areas of concern relative to composites and crashworthiness are as follows:

1.   Fuel containment in wet wings
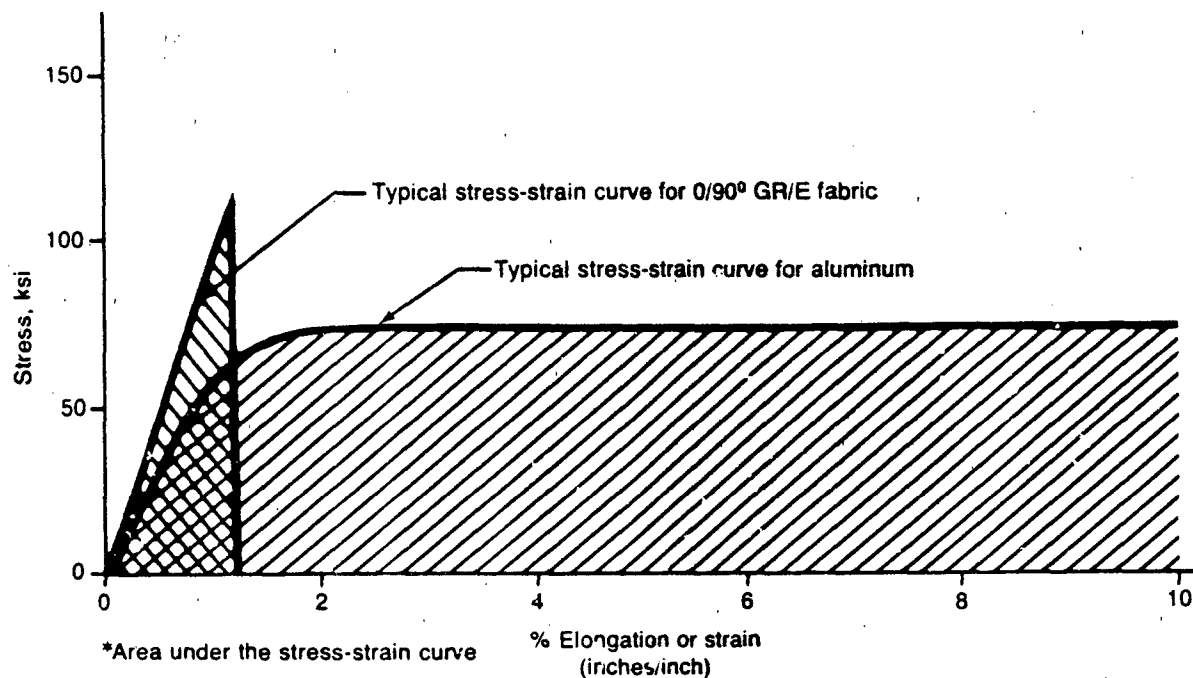
Figure 4.18–Comparison of Apparent Energy Absorbing Characteristics* of Graphite Epoxy Laminate and Aluminum
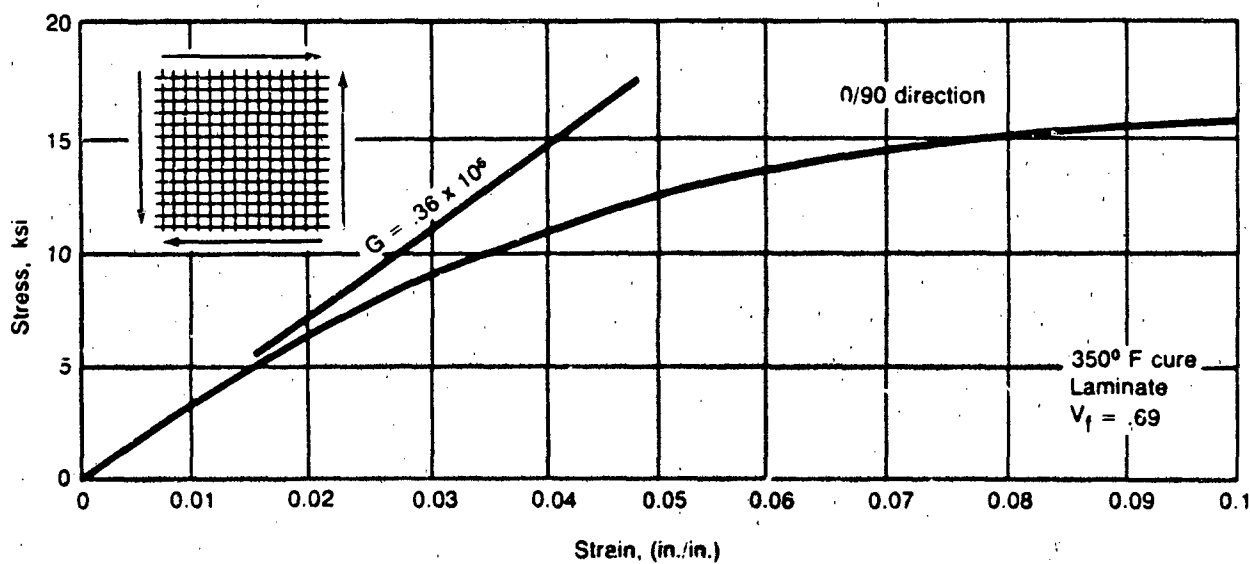
Figure 4.19–Shear Stress-Strain for Kevlar-49/5208 Style 181 Fabric at R.T., Dry

Figure 4-20.—Three Piece Failure of a Graphite Tension Specimen Illustrating Failure Induced Shock Wave Effects

Initiation phase

$E = \int F v \, dt$

$E = \int E_i + E_p$

Propagation phase

Ductility index

$DI = \dfrac{E_p}{E_i}$

Load, F

Time
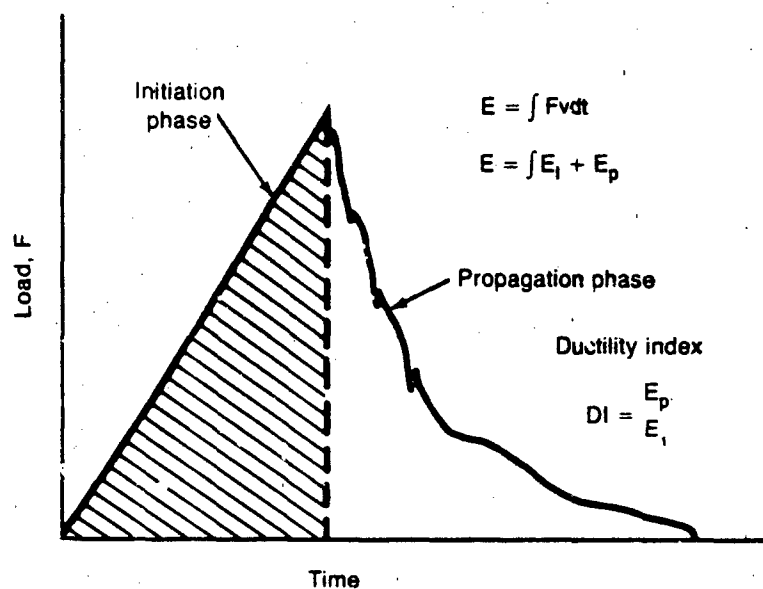
Figure 4.21. – Schematic Representation of Load History in an Impact Test

Table 4.7–Impact Properties of Unidirectional Composite Materials as Determined from Instrumented Charpy Test

Reinforcing Fibers	Apparent Flexure Strength ksi (MN/m²)	Total Energy Per Unit Area ft-lb/in.² (J/m²)		Ductility Index
		Dial	Oscilloscope	
HMS-graphite	125 (860)	3.8 (8 X 10³)	3.8 (8 X 10³)	0.0
20%kevlar 49 80% HMS-graphite	170 (1170)	34.3 (7.2 X 10⁴)	30.5 (6.4 X 10⁴)	.6
41% kevlar 49 59% HMS-graphite	141 (970)	46.7 (9.8 X 10⁴)	42.9 (9 X 10⁴)	4

The first value was based on the onset of nonlinearity. The number in parenthesis was based on maximum stress.

2. Smoke toxicity for interior cabin uses

3. Burn-through rates for fuselage applications

Fuel containment characteristics might be expected to be inferior to the metal wing. This is primarily due to the material being unable to plastically deform and still remain intact. Tear resistance of the material is high however, and failures tend to be of a delaminar nature. Thus, penetration damage may not be as severe. Also because of a lower density, structural inertia loads will be lower.

Smoke toxicity is not currently considered to be a problem. Risks are consistent with occurrence of other similar material now in the internal fuselage area.

Burn-through rates for composites are expected to be lower than for conventional aluminum. The graphite/epoxy will melt and the fiber char while the aluminum will melt. The much lower thermal conductivity of the composite (3 BTU/°F, hr, ft, ft^2, as compared to 80 for aluminum) will give it a decided advantage in deterring through-the-thickness heat transfer.

In order to assess the crash performance of composite structural components, it is necessary that the performance of current metal components be known quantitatively. Differences in crash response modes and the performance of the crash function may then be compared for each component. With improved analysis and test methods, design provision may be made for occupant protection.

Crash performance of advanced material components must be assessed in the context of the complete airframe. Implied reduction in energy absorption seen in coupon tests may be offset by design innovation in the structure, by use of parasitic crushable energy absorbers in key locations such as seats and lower frames, or may not even exist. The entire concept of occupant protection may need to be revised. Optimization studies of occupant protection strategies should be made. Research is needed to evaluate these advanced concepts.

5.0 CURRENT STATE OF CRASHWORTHINESS TECHNOLOGY

An overview of the current state of crashworthiness technology is presented in this section. The U.S. Army's Aircraft Crash Survival Design Guide (ref. 5), which provides a crashworthiness technical base for light aircraft and helicopters in military applications, is reviewed for applicability to commercial jet transport aircraft.

Analytical methods for modeling the occupant response to a crash environment are reviewed and assessed. Human impact tolerance is reviewed and problems of relating impact injury to engineering quantities are discussed. In addition, the applicability of generally recognized tolerance limits to the population of aircraft occupants is considered.

The status of analytical methods for treating nonlinearities in inelastic structural behavior and large deflection geometry is reviewed. A review of crash tests of complete aircraft and of experimental testing of structural components has been made. A survey of impact test facilities is presented and problems of testing complete commercial jet transport aircraft and structural components is discussed.

An assessment of current crashworthiness technology as applied to commercial transport aircraft is made. Requirements to improve crashworthiness engineering are presented and research to develop the necessary technology is discussed.

REVIEW OF U.S. ARMY CRASH SURVIVAL DESIGN GUIDE

The guidelines proposed in the new U.S. Army's Aircraft Crash Survival Design Guide have been examined to identify areas relevant to commercial airplanes.

The Aircraft Crash Survival Design Guide contains a summary of material that provides a background on crashworthiness in general. Specific application of the guidelines to commercial aircraft has been assessed. Appendix D presents a detailed synthesis of principles, practices and comments based on abstracting the Guide and incorporating other experiences, opinions and data.

The new U.S. Army's Aircraft Crash Survival Design Guide defines a number of goals that the U.S. Army desires to achieve in order to improve protection in Army aircraft. Evolution of these goals into clear-cut design criteria is a continuing process; this third update of the Guide incorporates feedback from interim experience, points out the likely need for design trade-offs more clearly than the previous editions, and as clearly points out compromises will likely remain after all possible trade-offs are complete. Two factors emerged from investigation of the Guide that bear comment: the autonomous role the Army has in exploring new concepts, including freedom to waive requirements; and the distinctions in vehicles and corresponding impact conditions from Army aircraft to large commercial aircraft.

First the autonomous role of the Army and the aircraft they fly gives them many options in exploring protective provisions. They have small vehicles (less than 20-passenger maximum capacity and more typically less than 5) with relatively clear-cut implications and ramifications for any changes that might be considered.

Additionally, as specification engineer, purchaser, and user, the Army is in a position to review trade-offs and waive goals, guidelines, and criteria when warranted. Under current regulatory procedures, this is not possible in the commercial environment; requirements, once established, may not be waived. This helps to clarify why goals, guidelines, and criteria are not clearly distinguished in the Army's Guide; such waiver authority makes it possible to emphasize

"maximum possible protection" and explore new concepts. Autonomous planning, purchasing, and user roles also make it more feasible to explore and appraise ideas that can not be easily determined or demonstrated by analysis or may be interpreted differently by individual reviewers (e.g., "provide as much protection as possible").

Other industry segments have a different circumstance; by design necessity, objectives are based on minimum acceptable requirements for adequate protection under given circumstances. Objectives are justified as actually being proven and beneficial, the waiver authority used in the Army does not exist in the commercial environment.

Secondly, there is considerable difference in likely impact characteristics between the small, rigid body aircraft used by the Army and the large, flexible body aircraft used commercially Army goals are based on systems which will suffer a larger range of impact attitudes and higher impact loads. For example, spin-in and rotor thrashing causes large lateral forces and upside down impacts that are essentially unheard of in large fixed-wing aircraft. Additionally, there is a marked difference in inherent energy absorbing features between the two airplane types. For example, the small airplane has a much smaller subfloor volume, fewer structural members, and a correspondingly more rigid structural area to absorb energy than exists for the large cross section of the flexible-body aircraft. Some of the resulting implications are inferred in the Guide. They point out, for example, that cargo tiedown criteria from the Army Guide are much larger than Air Force practices, but acknowledge that there is no statistical reason to change Air Force criteria.

The above describes some of the reasons to question direct transfer of guidelines or specifications from the Army Guide to commercial systems. Although many of the principles apply, are relevant, and are practiced, criterion bases are clearly different. Relevant criteria have been abstracted and collated from the Guide, and the resulting interpretation and commentary is presented in appendix D. The new Guide updates previous guidelines and goals based on Army's experience and their recognition of broader research and development activities over the last 10 years. In addition to data in the Guide, new information continues to be developed and earlier information continues to be clarified. Some such information is added to Guide information in appendix D (e.g., for tolerance and restraints).

The review of the Guide suggests some research topics and tools that are warranted, can be worked usefully, and will improve the technology for impact protection. Army goals to improve survivability for impacts of small aircraft include four major areas: (1) system design for structural integrity, energy absorption, and post-impact provisions; (2) design principles for impact protection via aircraft seats, restraints, litters, and padding; (3) modeling and testing methods for appraising impact loads, load paths and their effects; and (4) human impact tolerance and protection.

System design considerations in the Army continue to emphasize energy absorption and postcrash protection. Newly under consideration are possible ways to avoid reduction of and intrusion into occupiable volume caused by impact loading.

Energy absorption at the structural level remains a difficult concept to design and control. Absorbing provisions include gear, wings, fuselage, seats, litters, and restraints. Dynamic interactions at the system level are so complicated that final resolution of questions by the Army is still by test — full-scale drop tests are practiced. However, several computer models providing full system simulation have been under development for several years and are approaching stages where they should be challenged by attempts at real calibration and application.

Postcrash survival continues to receive very heavy emphasis in commercial systems. A major

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government/industry program is being carried out that has multiple objectives, including: to improve control of fire, develop new materials with improved characteristics, and develop a more heat resistant escape slide.

Evidence is starting to emerge suggesting feasibility for some concepts, but limitations remain to be resolved. Four examples are: (1) fuel inerting actuation by impact acceleration, may work on impact, but may also actuate at altitude in turbulence acceleration; (2) heat resistant slides are being developed, but some may not be stowable without major changes and others may have a short storage life; (3) some design features for control of fuel line disturbances are proving effective; (4) computer simulations of some processes are being explored, for example, simulation of fire propagation to improve understanding of and ability to control fires, and simulation of evacuation performance to provide an improved engineering tool. These are in the early exploration stages and should be continued.

Design principles emphasizing energy absorption concepts for seats, litters and restraint systems, are evolving at a more rapid pace. Load limiters are being considered as peak load alleviators to help maintain some degree of system integrity. They provide increased assurance the seat occupant will remain in place, and will not be subjected to loads exceeding his impact tolerance.

Modeling approaches simulating energy absorption characteristics at the seat-restraint level are demonstrating feasibility as a design tool (see Occupant Modeling Methods, following). They could be used to explore and develop effective energy absorbing seat-restraint concepts, and offer a cost- and time-effective approach to resolving energy absorption questions for the new composite materials technology. But stronger does not automatically mean safer, and a rigid 20 g seat will not necessarily provide the protection of a ductile seat that starts yielding at lesser loads. Composites do not feature the same ductilities as metals, and consequently possess different energy absorbing characteristics. Accordingly, use of composites may require alternative design concepts (e.g., different seat leg design) in order to benefit from the design advantages of composites without losing the energy absorption features of the earlier metal seating systems.

Modeling coupled with testing could become a meaningful combination for developing and evaluating system design concepts. Some existing models for structure, seat, restraint, and occupants could be calibrated to real world observations, integrated into a single system concept and used for advanced concept evaluations, for identifying specific data and test needs, and for predicting the outcome of major system tests. An overview of the models that could be used for this purpose is presented in table 5.1.

The desirable approach would be in two phases. First, experience with the various models is now sufficient, and it should be feasible to develop a detailed specification to define and develop a series of modules to permit exploration and development of individual elements that could be combined to estimate the performance of the occupant, restraint, seat, and structure. Second, it is necessary to develop and demonstrate calibrated three-dimensional performance against real test data, and define ground rules for appropriate use of 2-D and 3-D models. Some models, such as PROMETHEUS III, are two-dimensional but can demonstrate a high degree of accuracy in predicting to a test situation. Some added features may be needed to complete 2-D applications potential (e.g., in simulating an energy absorbing, deforming seat). From this result, and associated knowledge it will be easy to identify and develop 3-D refinements. The 3-D capability would complete occupant development needs and also help to discriminate when 2-D and 3-D models might be appropriate.

Human impact tolerance data continues to be in dire need. Data, indices, and estimates of tolerances are limited in both accuracy and scope of applicability. Obviously, tolerance limit data are not readily acquired. However, new data below the tolerance hazards continues to be generated and will be needed to reduce or eliminate the current constraints on data (see Human Impact Tolerance, and app. D).

Table 5.1–Plan for Developing Needed Models

Needed	Appraise	Develop specification	Develop/calibrate Models/modules	Predict to New tests
Model/module Purpose	Potentially Usable models*	Synthesize elements From known models	Refine synthesized Model(s)	
Occupant Simulation	PROMETHEUS III SOM-LA CALSPAN ATB (articulated total body)	OCCUI	Laboratory data Army drop tests NASA tests DC-7 test	Planned 1984 NASA-FAA Drone
Restraint Simulation	PROMETHEUS III SOM-LA ATB	RESTR 1	Constellation Test FAA tests	Test
Seat Simulation	PROMETHEUS III SOM-LA DYCAST KRASH ADINA	SET 1		
Structure/ Fuselage	DYCAST KRASH ADINA ACTION	STRUK 1		

*Improvements in existing models might be accomplished by including small packages such as the FEAP 74 structural contact model

More definitive research is needed for effective use of human tolerance data. Here, too, since tolerance limit research is impractical, models may be useful to explore tolerance in controlled tests to establish exposures in accidents and thus to update the data base using results from real accidents.

OCCUPANT MODELING METHODS

Numerous dynamic models of the human body have been developed for crash impact analysis to predict the response of the occupant, restraint and/or seat systems. One-, two-, and three-dimensional models have been developed. More broadly described in this present report are:

1. Dynamic Response Index (DRI) (ref. 6)
2. Seat Occupant Model: Light Aircraft (SOM-LA) (ref. 7)
3. PROMETHEUS (now PROMETHEUS III, ref. 8), two-dimensional, restraint performance integrated with body dynamics and other outputs similar to SOM-LA

OCCUPANT MODELING SUMMARY

Three occupant-simulation computer programs are evaluated in the following discussions for their ability to produce useful engineering data regarding relative safety of a restrained occupant: a 1-D model (DRI), a 2-D model (PROMETHEUS III) and a 3-D model (SOM-LA).

The one-dimensional model (DRI) is usable only for seat ejection evaluation and is of no use for evaluating the safety of commercial aircraft. The two-dimensional model (PROMETHEUS III) is suitable for producing sophisticated engineering trade-off data and is being used for this purpose, subject to the limitations imposed by the 2-D nature of the simulation. The 3-D model (SOM-LA) needs modeling improvements before being usable for engineering purposes. Needed improvements are technically difficult and fall into the realm of applied research. Although SOM-LA is not currently adequate for evaluation of restraint system performance, it provides a rough approximation of the gross motion of the occupant for purposes of approximating the dynamic loads on the structure. The possibility of merging these programs with a large finite-element computer program such as DYCAST will be also considered and a procedure for accomplishing the merging will be proposed.

PROGRAM CALIBRATION

Computer modeling of nonlinear transient structural dynamics is a relatively new technology, and standards defining a "good" structural dynamics computer program are still evolving. (Occupant-simulation is a special type of structural dynamics). As a consequence, each new structural dynamics computer program must individually earn acceptance in the engineering community before its calculations will be utilized by designers.

There are two aspects to acceptance:

1. The program must produce believable results. That is, predicted dynamics should appear reasonable and credible to the designer, and the designer should be confident that the program models the main dynamic effects. To enhance believability, the program output should contain, in readable form, information which assists the designer to understand the dynamic events (such as time histories of system forces). Graphic aids are also helpful.

2. Program accuracy must be demonstrated. That is, demonstration of capability to reasonably predict an actual test. Achievement of predictive accuracy is usually a very difficult and time

Figure 5.1—PROMETHEUS III Simulations

Added Features

Refinements Accomplished

New PROMETHEUS III Features

- Body dimensions
- Mass distribution
- Neck/waist stiffness
- Muscle tension
- Joint friction
- Pelvis – design interactions
  Angle
  Length
  Center of mass
  Stiffness
  Friction

- Back-stiffness
  Erectness
  Compression
- Belts-anchor points/angles
  Location/position on
  body
  Mass properties
  Damping
  Tension
  Stretch
  Slack
  Length
  Friction

- Seat pan – angle
  Friction
  Cushioning
  Viscosity
- Seat back – angle
  Cushioning
  Viscosity

- Submarining
  Pelvis rotation
  Buckle position

- Spinal changes
  9 segment articulation
  Compression/shear
  loads
  Compressible
  Lumbar/neck

- Improved input definition

- Improved restraint/
  seat modeling
  Optional anchors
  Added strands
  Harness/belt slip
  Friction
  Viscosity
  Cushing/Stretch

- Improved graphic/tabular
  output
- Added output force/Torque/
  Velocity/acceleration
- Initial positioning
  automated

Old - PROMETHEUS

- Features
  7 segment articulation
  Rigid hinge links
  Belts pinned to joints
  Limited belt anchors

**Parametric Sensitivity Analyses
for Refinement Included**

- Dimensions
  Shoulder
  Plevis

- Dummy flexing stiffness
  and compressibility
  Neck   Pelvis
  Back   Stomach

- Friction
  Webbing
  Seat pan
  Floor
  Shoulder
  Pelvis
- Webbing stretch

- Viscosity
  Dummy back
  Body contact points
  Webbing
  Cushions

- Resulting PROMETHEUS III features approximated CAMI conditions
  for data obtained, i.e.
  Dummy dimensions and mass distribution
  Pelvis compression
  Cushion friction
  Webbing stretch

**Calibration Status-Based on
CAMI Test Data**

- Within 10% on
  Gx chest, head
  Harness loads
  Belt loads

- Within about 10' on
  pelvis rotation

- Reasonable time history for
  accelerations, loads

- Time history trends reasonable,
  loads low for G_z, chest, head

Figure 5.2 — PROMETHEUS III Simulations Capabilities and Calibration Refinements

consuming process for occupant simulation codes because of the nonlinear nature of the problem and the difficulty in obtaining measured values for input dynamic parameters.

One approach was applied in evolving a calibrated level of performance for PROMETHEUS II. Instrumentation data from several sled tests were obtained from CAMI and physical data for the anthropomorphic dummies were obtained (limb weights, measurements, and spring constraints). These were systematically refined by sensitivity testing so that properties could be estimated where measured data could not be found.

One of the CAMI tests was then simulated by PROMETHEUS. When the initial simulation did not provide satisfactory correlation with test data, the problem was attacked from two directions. First, it was evident that the restraint system model in PROMETHEUS was inadequate, so a more sophisticated mathematical model of the lap belt and shoulder harness was developed and added to PROMETHEUS. For example, the lap belt was refined to permit the slipping associated with submarining, the shoulder harness was refined, and chest/shoulder flexibility was added to appropriately incorporate harness/body interactions and slipping of the harness on the shoulder.

The second approach, which was attempted concurrently with the first, was to parametrically vary the mechanical properties of the simulated occupant (such as neck stiffness and damping) in PROMETHEUS simulations and note the resulting trends. Parametric variations helped provide a "feel" for the occupant dynamics and served as sensitivity studies to identify the important dynamic parameters. Some dynamic effects were observed which were not influenced by the parametric variations. Additional modifications were made to the mathematical modeling in PROMETHEUS and parametric evaluations completed to approximate these effects. Additional cycles of modeling improvements/parametric variations continued until correlation with actual test data was achieved. The resulting modeling changes to PROMETHEUS were quite extensive; so much so that the correlated model was renamed PROMETHEUS III. Figure 5.1 summarizes parametric variations and modeling changes required to achieve calibration. After calibration, an independent test case was simulated with PROMETHEUS, producing good agreement with actual test results involving a real Part 572 dummy in sled testing. Figure 5.2 indicates the correlation finally achieved.

REVIEW OF OCCUPANT-SIMULATION COMPUTER PROGRAMS

Three occupant-simulation models are reviewed below. These are a one-dimensional model (the spring-mass model associated with the Dynamic Response Index), a two-dimensional model (PROMETHEUS III), and a 3-D model (Seat-Occupant Model: Light Aircraft).

The models are examined from two viewpoints: first, as a tool for engineering design of a seat/restraint system; and second as a possible candidate for integration into a large structural dynamics simulation computer program, in order to model the complete system (aircraft, seat and occupant) in a single simulation.

ONE-DIMENSIONAL MODEL—DRI

A one degree of freedom dynamic-response model of a human occupant has been proposed (ref. 6). The model consists of a simple linear spring and damper and a point mass. The spring is sized by the compressive stiffness of the lumbar vertebrae and the damper is sized by human vibration tests.

The DRI is an injury scale associated with this model. The DRI for a deceleration pulse is the ratio of the peak compressive spring force which occurs when the model is excited by the pulse to the

weight of the point mass. To associate tolerance levels with the DRI, the DRI was calculated for existing ejection seat designs. Computed DRI values were plotted against the percentage of ejections in which spinal injury occurred; the curve thus obtained represents an approximation of injury probability as a function of DRI.

Both the simple occupant model on which the DRI is based and the DRI itself are very limited in application. The simple model could only be used for cases in which the loading is purely vertical, that is, $+G_z$ such as in ejection seats. It is obviously not applicable to model a restrained occupant under forward loads; in this case, the main effect is the combined stiffness of the restraint system and the occupant's pelvis/chest. Even for $+G_z$ acceleration, the model is difficult to use since potentially significant effects are neglected, such as the effect of seat pan stiffness.

The DRI is based on a model which does not adhere closely to the actual dynamics of an ejection. Seat pan stiffness is not considered nor is distribution of body mass along the spine nor the weight of the occupant. Thus the DRI can be expected to produce useful data only in crashes which are similar to a seat ejection—that is purely $+G_z$ acceleration, seat pan stiffness similar to the stiffness of a fighter pilot's seat and the occupant tightly restrained.

The U.S. Army's Aircraft Crash Survival Design Guide says of the DRI:

> "Although the Dynamic Response Index (DRI) ... is the only model correlated extensively for ejection seat spinal injury prediction, it has serious shortcomings for use in accident analysis. It assumes the occupant to be well restrained and erect, so that the loading is primarily compressive, with insignificant bending. Although such conditions may be assumed for ejection seats, they are less probable for helicopter crashes, in which an occupant may be leaning to either side for better visibility at the time of impact. Further, the DRI was correlated for ejection pulses of much longer duration than typical crash pulses.
>
> "A more detailed model of the spinal column would yield more realistic results, but injury criteria for the more complex responses have yet to be developed. Consequently, the DRI is not recommended as the criterion for use in designing crashworthy seats."

REVIEW OF PROMETHEUS III AND SOM-LA

The following discussion reviews and compares the 2-D program PROMETHEUS III (ref. 8) and the 3-D Seat-Occupant Model: Light Aircraft (SOM-LA) (ref. 7).

PROMETHEUS III was developed at Boeing in a series of applications for different purposes, starting from the Dynamic Science program SIMULA. The focus of PROMETHEUS III, has been on accurate modeling of the occupant and restraint system. PROMETHEUS III has since been used extensively to develop data for assisting in engineering design decisions. SOM-LA development was sponsored by the FAA through a series of contracts with various companies and universities. Emphasis in SOM-LA development has been on the detailed seat model. An improved version of SOM-LA, termed MSOM-LA was completed under number DTFA03-80-C-00098. The occupant model has been upgraded in MSOM-LA.

DEVELOPMENT OF BASIS OF EVALUATION

Occupant-simulation using PROMETHEUS III computer program has been developed and demonstrated sufficiently to be used in the engineering design process. This experience is drawn upon to establish criteria for continued evaluation of occupant-simulation computer programs.

Design questions for which PROMETHEUS III simulations provided engineering data were quite varied; the common denominator being relative occupant safety. Due in part to the limitations of existing human tolerance data, it is rarely possible to predict with certainty whether injury would have occurred in a given crash on the basis of a computer simulation. Similar questions may also be unanswered in dummy tests. In most cases, computer simulation is the only practical method for obtaining design data for specific questions, and on a timely basis. To be usable for design, an occupant-simulation computer program requires two major attributes.

First it must be able to model a general structure (not just a seat), and be able to model contact between the occupant and any part of the structure. (For example, impact of an occupant with the seat ahead).

The second feature is that the program must provide data which may be used for estimating comparative injury potential. This means that:

1. The program must have been calibrated by predicting test data (preferably from live human tests).

2. Time histories of forces acting on individual body segments of the occupant model should be printed and/or charted.

3. Time histories of torques acting in joints of the occupant (e.g., the elbow) should be printed and/or charted.

4. Time varying internal loads acting on flexible body segments (such as the lumbar spine) should be printed and/or charted.

Of course, the standard software features relating to ease of program use are also desirable—that is, ease of input, automatic data checking, legibility of output, and availability of graphic aids.

COMPARATIVE EVALUATION OF PROMETHEUS III AND SOM-LA

Figures 5.3, 5.4 and 5.5 constitute checklists of features needed for engineering design usage of occupant-simulation computer programs. Checklist items were obtained pragmatically from experience in using PROMETHEUS III to develop design data. The amount of use of PROMETHEUS III justified incorporation of most checklist items into this program; consequently the lists serve mainly to indicate desirable improvements in SOM-LA. The main improvement in MSOM-LA is an improved seat, capable of modeling energy absorption. The occupant model has also been improved by the incorporation of a flexible segment representing the lumbar spine.

The major "deficiency" in PROMETHEUS III is that it has only been possible to perform limited, exploratory calibration against live human test data and for similar reasons limited exploration of seat model dynamics. Added calibration of this type is desirable. A benefit of 2-D modeling is that mechanisms within the 2-D PROMETHEUS III model are easier for the analyst to comprehend than those within a 3-D model, giving an advantage for initial use of a 2-D model in calibration efforts. Other than development, which may be required to achieve such calibration, further model evolution must consider limitations intrinsic to the 2-D nature of the model and distinguish the conditions for using a 2-D or a 3-D model. Of course, current uncertainties in the level of human tolerance to transient loads are a constraint that must be observed for either 2-D or 3-D models.

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Feature	Prometheus II'	SOM-LA	MSOM-LA (Note 1)
I Occupant			
Segment masses, length, inertias, c.g.'s.	I,D	I,D	I,D
Mechanical properties of joints	I,D	D	D
II Restraint system			
Mechanical properties of lap belt	I,D	I	I
Mechanical properties of harness	I,D	I	I
III Seat			
Geometry	I,D	I	I
Construction	I,D	D	I
Mechanical Properties	I,D	I	I
IV Crash Pulse	I,D	I	I
VI Interactive (conversational) input feature	X	-	-

I = Input, D = Default (i.e., supplied by program)

Note 1: It is assumed that the MSOM-LA input is essentially the same as the SOM-LA input.

Figure 5.3–Comparison of Program Input Features

Feature	Prometheus III	SOM-LA	MSOM-LA (Note 1)
I Occupant			
Segment cartesion position, velocity, acceleration	X	X	X
Segment angular position, velocity, acceleration	X	–	–
Forces on segments	X	–	–
Joint torques	X	–	–
Spinal loads	X	–	–
II Restraint system			
Lap belt load	X	X	X
Harness load	X	X	X
Belt Slip	X	–	–
III Seat			
Cushion forces	X	X	X
Reactions	X	X	X
Nodal forces	X	–	–
Element forces	X	–	–
IV Crash pulse	X	X	X
V Printer plots			
Acceleration traces (vs time)	X	X	X
Snapshots of victim/seat.	X	–	–
Locus of segment c.g.'s as Functions of time	–	X	X

Note: It is assumed that the output features of SOM-LA and MSOM-LA are essentially the same.

Figure 5.4–Comparison of Program Output Features

Feature	Prometheus III	SOM-LA	MSOM-LA
I Occupant			
Spinal articulation	5 links	4 links	5 links
Flexible lumbar link	X	–	X
Flexible cervical link	X	X	X
Automatic initial position Generation	X	X	X
Compressible chest, pelvis,	X	–	–
II Restraint system			
Realistic friction	X	–	–
Free to slide on victim	X	–	–
Webbing stretch	X	X	X
III Seat			
Finite element model	X	X	
Bar elements	X	X	X
Beam elements	X	X	X
Plate elements	–	X	X
No. of elements in typical seat model	6*	60	60
Cushion	X	X	X
Eergy absorption	X	X**	X**
Aircraft interior modeled	X	–	–
IV Crash pulse			
Translation components	X	X	X
Rotational components	–	X	X
V Calibration against experiment			
Anthropomorphic dummy	X	***	***
Live human	***	–	–

X   Capability available

*   Growth available

**   According to the SOM-LA developer, Dr. David Laananen, this feature does not work in SOM-LA but does in MSOM-LA.

***   Preliminary calibration accomplished.

Figure 5.5–Comparison of Basic Modeling Features

SOM-LA could benefit from both human data calibration and model improvement (from the standpoint of usefulness for engineering design). There are two major modeling deficiencies — the restraint system model and the difficulty of modeling nonstandard seats and structure. Both represent difficult modeling problems in a 3-D environment, and methods developed to simulate these features in the 2-D PROMETHEUS III computer program can not be readily generalized to three dimensions.

SOM-LA has a very primitive restraint system model. Restraining belts are pinned to the body, so realistic modeling of a restrained occupant is impossible. SOM-LA also has limited flexibility in the type of restraint system which may be modeled. Nonstandard configurations, such as restraint system with crotch or thigh straps could not be simulated. In addition, harness friction is implemented incorrectly (friction is crudely and incorrectly simulated by reducing tension in the strap segment running from lap belt to shoulder by 12%). Another serious defect is that chest compressibility (which effects shoulder harness loads) is not modeled.

Accordingly, this simple restraint system model is inadequate for engineering design use for evaluating restraint system performance. It introduces uncertainty into predicted body loads and accelerations, since dynamic performance of the restraint system is one of the primary sources and conduits of transmission of crash loads to the occupant.

The second major SOM-LA deficiency is the limited simulation of structural configurations. It is possible that more generality is available in MSOM-LA. In addition, it is desirable that MSOM-LA be capable of simulating contact between the occupant and an arbitrary structure (e.g., the back of the seat ahead). This finite-element "contact problem" is difficult and is the subject of current research (e.g., ref. 9).

In addition to these research improvements, several improvements would enhance usability of the code:

1.   Calculate and display time histories of loads acting on the occupant (e.g., spinal loads, segment forces, joint torques).

2.   Improve the algorithm for computation of joint torque.

3.   Add printer plot "snapshots" of seat and occupant for credibility and for appraising occupant location at selected times (two views) for comparison with slow motion movies.

INCORPORATION OF SOM-LA INTO LARGE CRASH DYNAMICS CODE

It may become necessary to predict dynamic interactions of occupant and floor structure. Simple predictions may be possible with SOM-LA. Action has been started within the government to combine the 3-D SOM-LA with a large finite-element computer program (e.g., the 3-D DYCAST) in order to model an aircraft crash in a single simulation to more properly couple the dynamics of occupants and aircraft structure. To accomplish this, it is suggested that the occupant/restraint model be extracted from the SOM-LA occupant/restraint/seat model and packaged as a super-element. The occupant super element would then be inserted into the large finite-element programs as a module. Although, as noted, improvements in the SOM-LA restraint system model are needed to model occupant dynamics accurately. The existing SOM-LA occupant/restraint system model would probably be adequate for the purposes of calculating the gross dynamics of the seat system.

The finite-element code would be utilized to model the seat — that is, the SOM-LA seat model would not be used. (This presumes the development of a general contact model to simulate forces acting

between the seat and occupant.) The contact model would be used to simulate seat cushions. This concept has three advantages:

1. Simulation of multiple occupants becomes possible (e.g., a "triple" seat).

2. Synchronization of the numerical integration schemes (i.e., the procedures for solving the equations of motion as function of time) in SOM-LA and the finite-element program is not required. The integration scheme of the finite-element program is utilizea for both occupant(s) and structure.

3. The capability of the finite-element computer can be employed to model general seat designs.

It would be possible to use the large finite-element program to model the occupant. The advantage of the super-element is that occupant modeling requires features that are not needed in general finite-element modeling of structures, such as limits on angular motion of limbs at joints. Moreover, occupant modeling is specialized, and correct mechanical parameters describing the occupant are not widely known (in some cases supportive data are not known at all and parameters must be inferred by parametric sensitivity testing). Thus it would be difficult for a nonspecialist to construct an accurate model.

Additional effort would be required to make the occupant super-element work; provision for transmitting input data to the super-element and obtaining printout of detailed occupant time histories is required. In addition, graphics output from the finite-element program (if graphics post processing is available) must be adjusted to draw the occupant(s) in addition to the structure.

The same procedure could be used to lift the 2-D occupant model from PROMETHEUS III if a 2-D crash simulation were employed. However, there is little benefit to be obtained from using such a model in an overturning or cartwheeling light aircraft where violent interactions of all three dimensions of motion would be occurring.

HUMAN IMPACT TOLERANCE

In simulating the crash of a vehicle with human occupants, either by actual test or computation, the capability of estimating the degree of injury sustained by the occupant is highly desirable. Various scales have been proposed for this purpose and these are evaluated below. At present, skeletal fracture tolerances provide the best means for predicting injury (including head injury).

Human injury is a complicated biological process; causative physical mechanisms are often not well understood, and consequently, traditional engineering methods are difficult to apply. Physiological changes are also known to occur in response to crash loading (e.g., change in pulse rate), further complicating analysis.

To fulfill the researcher's need to quantify injury, a number of injury scales have been devised. These scales are based on clinical data or physical measurement, such as, head acceleration history. These scales are generally intended to estimate physiological trauma rather than skeletal damage The better known of these scales will be described.

A note of caution is appropriate at this point; currently existing injury scales represent some form of empirical correlation between injury and measured quantities. Correlation is not directly based on the mechanism which actually causes injury; rather, statistical correlation with parameters considered likely to be implicated is established. Use of an injury scale outside the conditions for which correlation was established is risky. Moreover, there is always uncertainty in the accuracy of the basic data since injury data cannot be developed from experiments with live people, but must be inferred from cadaver or animal tests.

Differences between individuals further complicate matters. Despite these limitation, injury scales provide a method for assessing injury in a crash simulation. Such scales provide a rational (although possibly inaccurate) means for comparing simulation results.

In contrast to physiological damage to organs, prediction of skeletal injuries is amenable to ordinary engireering methods. Mechanical properties of bone have been determined experimentally. Standard engineering analysis techniques might be employed to determine the extent of bone damage in a particular situation. Although there are differences in bone strength and size between individuals, and live human bone cannot be tested, extensive theoretical knowledge of structural dynamics permits much greater confidence in the accuracy of such computations than in the accuracy of injury indices.

Bone damage is only part of injuries, and not necessarily the most serious part. Concussion, for example, can occur without accompanying skull fracture. Moreover, the accuracy of engineering analysis of the skeleton depend upon accurate computation of forces acting on the skeleton, such as restraint system and contact forces. Contact forces are particularly difficult to obtain, since the contacting portion of the human body generally has irregular geometry and the mechanical properties of the bone, flesh and contacted structure all interact to determine the dynamically varying force acting on the skeleton. Occupant-simulation models discussed herein (e.g., PROMETHEUS III, SOM-LA) do not model the skeleton in sufficient detail to accurately predict bone fracture. However, structural loads are calculated in these programs (e.g., lumbar axial load), and these provide a rough measure of the likelihood of skeletal damage. Chapon (ref. 10) gives an excellent summary of experimentally determined fracture loads.

Injury scales can be grouped into three classes: (1) scales based on clinical evaluation of actual injuries, (2) "whole-body" scales, and (3) scales developed to predict a particular type of injury.

The first group of scales is intended to quantify clinical diagnosis of the injuries sustained by a particular person. This provides a yardstick for comparing the severity of injuries occurring in different accidents even though the injury mechanisms may be quite different. Such scales are necessarily subjective; their main use is in accident investigation. A well known scale of this type is the Abbreviated Injury Scale (AIS), as defined in reference 11. Obviously, scales based on clinical diagnosis are of very limited use to the modeler.

Whole-body tolerance scales are based on empirical observations, sometimes including the results of animal tests. These scales attempt to assess "survivability" based on a gross description of the impact deceleration pulse using parameters such as peak deceleration, duration of deceleration and onset rate. A difficulty in using published whole-body scales is that authors often do not distinguish between peak deceleration and average deceleration (which may of course, be quite different). These scales refer to the crash load delivered to the seat, and do not directly consider occupant/restraint system response. Separate scales are available for different loading conditions (e.g., G_x, -G_x, G_z), but no provision is made for combined loading (such as simultaneous -G_x and G_z deceleration). Whole-body scales might be useful in early preliminary aircraft design; they are of no use in detailed occupant models such as PROMETHEUS III or SOM-LA.

Injury scales in the third group are intended to estimate damage of a particular type. DRI is an example of this type of scale. The DRI is intended to predict injury to the lumbar spine during vertical (G_z) accelertion.

CONCUSSION SCALES

Several widely publicized scales in the third group with potential for use with occupant models are

designed to predict concussion. The mechanism causing concussion is not well understood, although there has been extensive investigation. It is known that concussion can result from either linear acceleration (e.g., from head impact) or else from rotational acceleration (i.e. whiplash). To date, most investigations have focused on either linear or rotational acceleration. Combined effects have also been investigated, but data is scarce.

CONCUSSION CAUSED BY TRANSLATIONAL ACCELERATION

A widely used measure of human tolerance to linear acceleration is the Wayne State Curve (WSC) (fig. 5.6 and ref. 12). The WSC predicts that acceleration pulse magnitude is more important than pulse duration in causing concussion.

The following description of derivation of the WSC is paraphrased from Hodgson, et al. (ref. 13). The basic experimental work on which the WSC depends was a study of concussion on mongrel dogs (refs. 14 and 15). Deceleration pulses of systematically varied magnitude and duration were applied to the brains of 72 dogs, and a concussion tolerance curve for the species was then obtained. It was postulated that the same curve shape would be valid for humans. Cadaver skull fracture data was employed to determine the shape of the human curve for pulses less than 10 ms in duration (clinical experience indicates that concussion normally accompanies skull fracture). The long pulse end of the WSC (duration greater than 100 ms) was estimated from acceleration sled rides of Stapp and other volunteers (ref. 16). The intermediate range of the curve was estimated from cadaver drop tests onto automobile dash panels.

It should be noted that data on which the WSC is based utilize a single acceleration pulse; multiple blows are not used and influence of pulse shape is not considered. Moreover, the shape of curve is not well supported by experimental evidence for pulse durations greater than 10 ms.

Newman (ref. 12) reports, regarding the Wayne State Curve, "The validity and usefulness of this tolerance curve have been questioned on a number of grounds including:

1. "The ordinate's effective acceleration was poorly defined. Patrick, et al. (ref. 17)[*], had stated: 'The ordinate is Effective Acceleration which is based on a modified triangular pulse in which the effective acceleration is somewhat greater than half the peak value. Therefore, triangular or sinusoidal pulses of equal area and higher peak magnitude are in accord with the experimental evidence from which the Tolerance Curve is derived.' Later (ref. 18) it was stated: 'Effective acceleration is computed by dividing the area under the acceleration time record by the time. A judicious analysis of the geometrical shape of the curve is important. For instance, high amplitude spikes of short duration (less than 1 millisecond) should be disregarded.' More recently, (ref. 19) effective acceleration has been equated exactly to the time averaged acceleration over the duration of the pulse."

2. "The head impact data is not applicable to blows other than those to which the experimental animals and cadavers were subject. To quote Gurdjian, et al. (ref. 20): 'It should be pointed out, however, that care should be taken in using a tolerance curve of this nature. It is entirely possible that a curve of the same shape, but having different values for the acceleration magnitude, could very well be shifted up or down depending upon the point of impact and the blow direction.' Stalnaker, et al., (refs. 21 and 22) have confirmed that there are significant differences in the response of human and monkey heads to lateral and longitudinal impacts."

3. "Because the WSC was based on measured acceleration time histories of a point on the head essentially opposite the forehead blow location; skull vibration may have had a significant effect on the apparent head acceleration. Hodgson and Patrick considered this question in

[*] Reference numbers have been converted to correspond to the numbering sequence of this document.

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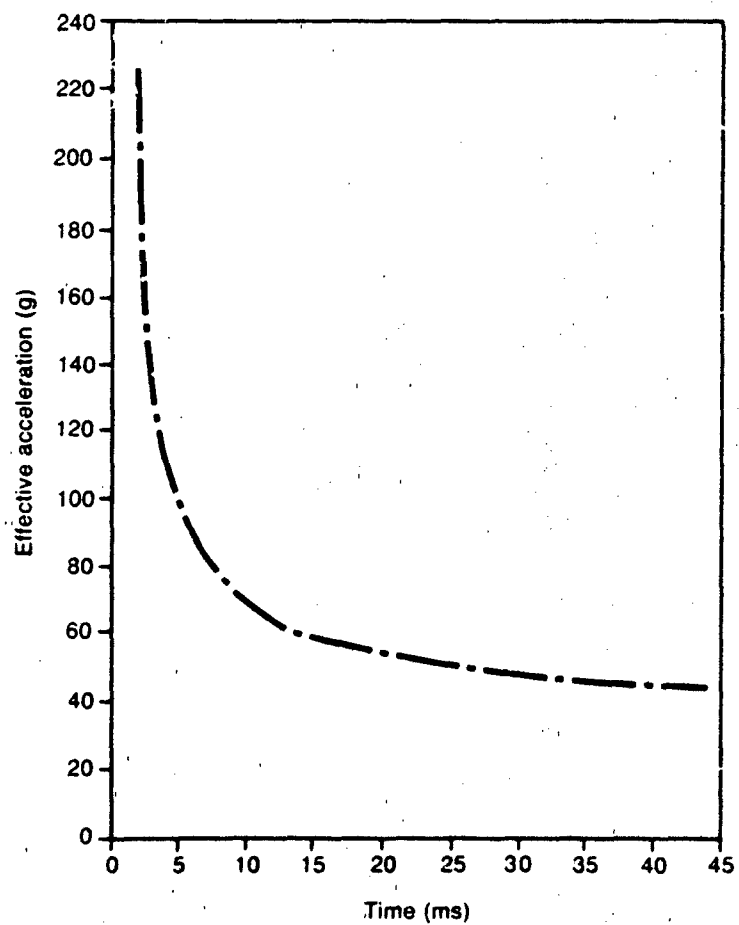
Figure 5.6–Wayne State University Cerebral Concussion Tolerance Curve

1968 (ref. 23) and it is now customary to use two biaxial accelerometers mounted to the side of the head (ref. 13). As suggested by Mertz (ref. 24), assuming rigid-body mechanics, the acceleration of the center of gravity of the head can then be determined.

4. "The WSC has never been verified for living human beings, although recent indirect efforts through accident simulation (ref. 25) have been attempted."

Several injury indices have been suggested based on the Wayne State Curve. These are the Head Severity index (ref. 26), the Head Injury Criterion (refs. 12 and 27) and the J tolerance (ref. 28). All three tolerances agree roughly with the Wayne State Curve for short duration frontal head impacts (i.e., 10 ms duration, half sine wave shape). The criteria give different results for multiple pulses or irregular pulses, and the relative merits are hotly debated. However, little clinical evidence is available to indicate whether any of the scales (or indeed the Wayne State Curve) is valid for these conditions.

The widely used Swearingen diagram of acceleration tolerance of the facial bones (figure 5.7 and ref. 29) actually represents fracture data under dynamic loading. The acceleration tolerances given should be multiplied by the head weight to obtain fracture tolerance. Thus the fracture tolerance of 30 G given for the nose means that the nose will fracture when the nose is struck with sufficient force to impact 30 G acceleration to the whole head, which would be a force of 300 lbs., assuming a ten pound head weight. It does not mean that whenever the head is accelerated to 30 G (e.g., through whiplash) that nose fracture occurs.

CONCUSSION CAUSED BY ROTATIONAL ACCELERATION

Concussion can be induced by head acceleration pressure in contrast to impact loads; a tentative estimation of human tolerance to rotational acceleration was made by Omaya, et al. (ref. 30). A tolerance curve was experimentally determined for rhesus monkeys, and the human tolerance curve was inferred from monkey curves by scaling the acceleration axis by $r^{2/3}$, where r is the ratio of the weight of the rhesus monkey brain weight to the human brain weight (fig. 5.8). Omaya, et al. stated that additional experimental confirmation is required before use of the curve is justified. As far as can be determined, no confirmation data has been published to date. Thus figure 5.8 must remain tentative.

STRUCTURAL MODELING COMPUTER PROGRAMS

INTRODUCTION AND RECOMMENDATION

Impact dynamics of a real crash involving complicated structural design are too complex for manual analysis, however, modeling methods offer an eventual capability that could provide a simulation of all dynamic interactions.

Simulation may be by analytical models, scale models, computer models, and full-scale tests in order to provide both observation of complex interactions and a rational basis for the sequencing of events, loads, and modes of failure.

Numerous computer simulation models, in particular, are being developed for use in simulation evaluations. Some are being developed for support of preliminary design studies, others for more sophisticated uses. The four main classes of models that are used include:
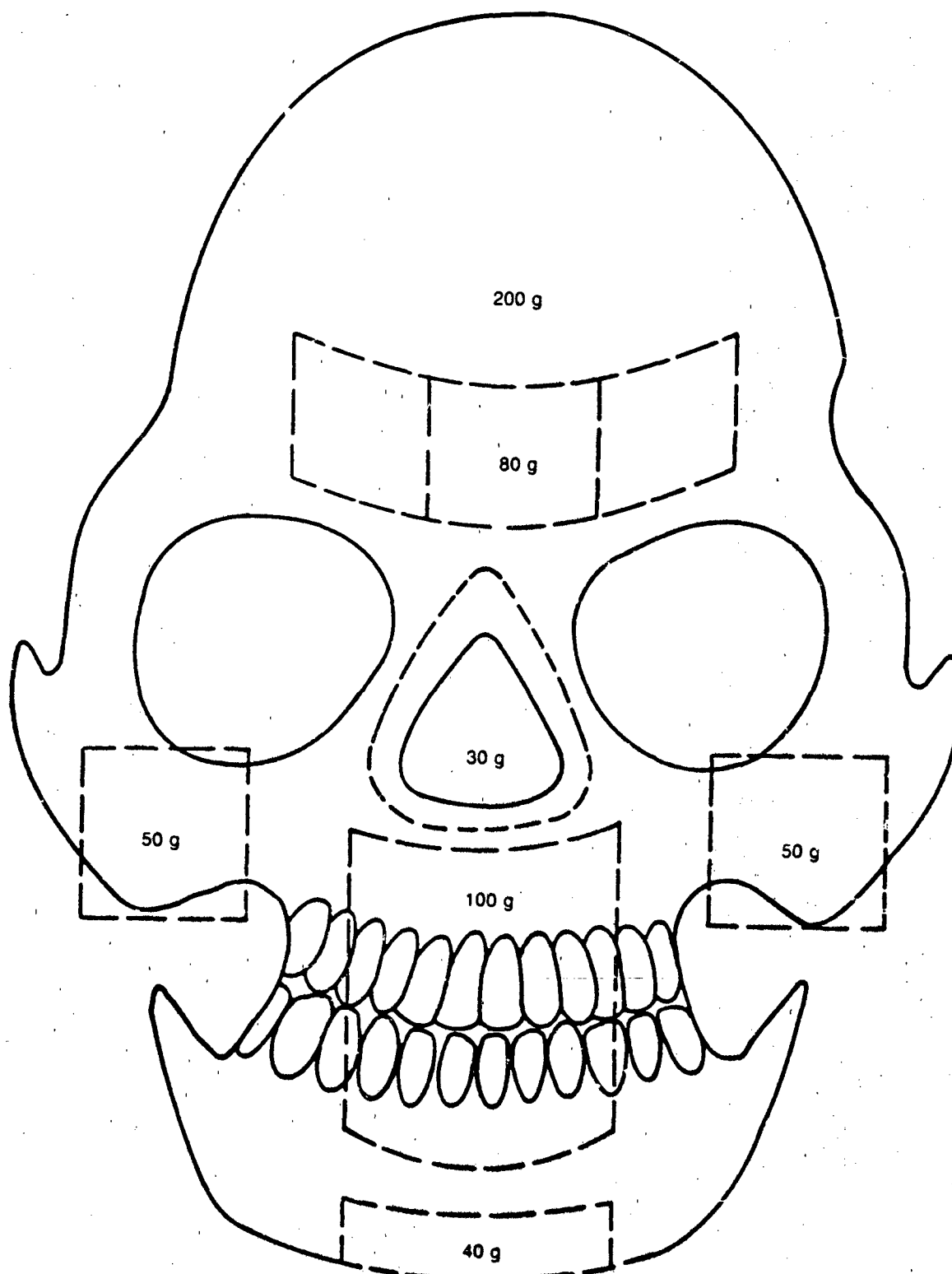
Figure 5.7 – Summary of Maximum Impact Forces on a Padded Deformable Surface
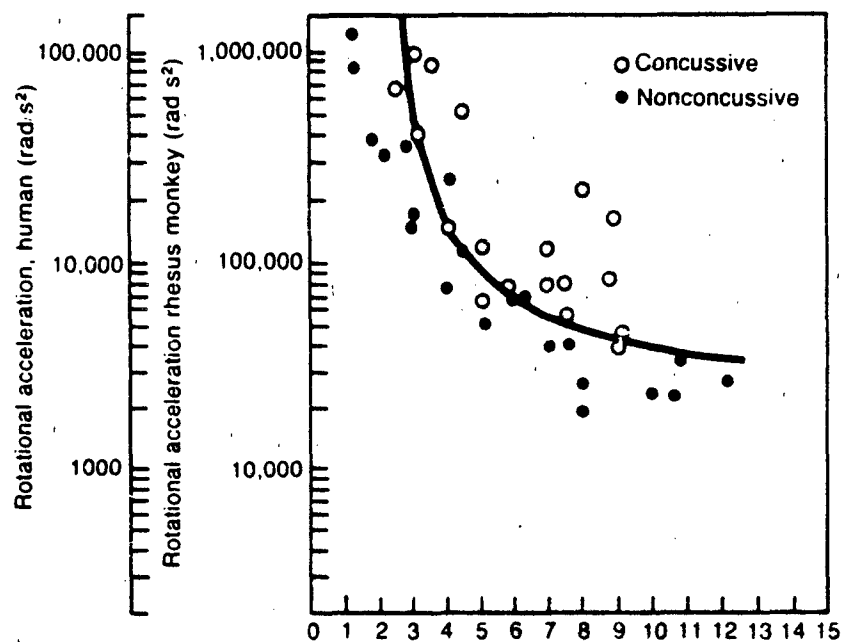
Note: The human tolerance scale was obtained by multiplying the rhesus monkey scale by $(M_{human}/M_{monkey})^{2/3}$ This scale must be regarded as an untested hypothesis at this time.

Figure 5.8-Cerebral Tolerance to Rotational Acceleration for Rhesus Monkeys

1. Generalized spring mass models

2. Frame type models

3. Hybrid models

4. Finite-element models

Spring-mass models and frame models use a very simple model of the structure to estimate crash behavior. Frame models differ from spring-mass models in that beam elements are employed in modeling, in addition to springs and point masses. Hybrid models use static test data in conjunction with a spring-mass model or frame model to predict dynamic behavior of a structure. Finite-element approach uses more formal approximation approaches for more discrete definition of structural representation and properties. Finite-element models tend toward increasing complexity and computational cost. However, none of the modeling procedures is totally free of testing requirements and analytical judgment. The reason is the extremely complex process for vehicle structure deformation under crash loading, which involves:

1. Transient, dynamic behavior

2. Complicated framework and shell assemblies

3. Large deflections and rotations

4. Extensive plastic deformations

A number of computer programs have been developed to simulate nonlinear dynamic response of structures. These programs are categorized as "hybrid" and "purely mathematical finite-element models." Brief descriptions of some of these programs are given, and three of the programs (KRASH, DYCAST and ADINA) are evaluated in more depth. It is concluded that none of the programs has all needed features.

HYBRID VS. PURELY MATHEMATICAL

Workers investigating the behavior of structures in crash situations often categorize analysis methods as "hybrid" or "purely mathematical." A definition of these terms is given in Winter, et al. (ref. 31).

> "Hybrid — A combined experimental and mathematical method, such as the lumped mass/spring method, in which the structure is divided into a number of relatively large sections or assemblies that are usually idealized as beam/springs whose deformation characteristics are found from static deformation tests or separate engineering analyses. Structural mass is lumped with nonstructural masses at the beam ends, and the equations of motion of the mass points are solved numerically.

> "Purely mathematical—As in the finite-element method, in which structure is divided into its individual natural components (beams, stringer, skin panels, etc.) which are then subdivided into appropriate structural units called elements. The deformation characteristics of each component are calculated theoretically from its material stress/strain curve and its changing shape and position in the structure. The structural mass is placed at nodes at each element boundary and is therefore distributed throughout the structure. The equations of motion of the elements are then solved numerically."

Hybrid technique permits use of simpler, less expensive structural models. A hybrid model is particularly useful when many simulations of the same structure are to be made. Occupant models in occupant crash simulation (e.g. PROMETHEUS III, SOM-LA, Articulated Total Body (ATB)) are almost always hybrid models—for example, the lumbar spine is represented as a single beam rather than an assemblage of vertebrae, discs, and ligaments.

In fact, purely mathematical methods require considerable engineering judgement, even art, to use successfully; the distinction between hybrid and purely mathematical is more nearly a matter of degree than a real distinction.

Researchers in the field note that both approaches are necessary. Hayduk, et al. (ref. 32) conclude, after comparing the hybrid program KRASH with the purely mathematical finite-element programs ACTION and DYCAST:

> "A hybrid computer program (KRASH) and two finite-element computer programs (ACTION and DYCAST) have been used to analyze a section of a twin-engine, low-wing airplane subjected to a 8.38 m/s (27.5 ft/s) vertical impact. A vertical drop test experiment was performed at the NASA Langley Impact Dynamics Research Facility. The results of the analyses demonstrated the capability of all three computer programs to quantitatively simulate the significant dynamic response of aircraft structures under impact loading."

> "Because of the variation in complexity of the KRASH lumped-mass model (177 DOF (degrees of freedom)) and the ACTION (336 DOF) and DYCAST (493 DOF) finite-element models and solution methods, there were two orders of magnitude difference in analysis cost. Consequently, the lumped-mass hybrid approach should be used in conjunction with the finite-element approach, the two approaches complementing each other. The lumped-mass hybrid approach can be used to evaluate gross vehicle response, design trends, structural design and impact parameters studies, and gross energy dissipation. The finite-element approach should be used for analysis of designs where the detailed behavior of individual components are critical, for obtaining detailed loads required for input to other analyses, such as a lumped mass-hybrid technique or an occupant simlulator, and for detailed stress analysies in sizing of structural components."

Cronkhite, et al. (ref. 33) agree with the Hayduk conclusions. Cronkhite states:

> "Computer analysis methods are still being verified for metal structures, while composites will need special treatment because of their low strain-to-failure characteristics. At present, both the hybrid (KRASH) and finite-element (DYCAST) structure crash analysis methods are needed. The hybrid type of analysis is useful for preliminary design analysis and for parametric studies of the entire airframe. The finite-element analysis method has the potential for detailed structure analysis directly from drawings and may be used to develop inputs to the hybrid type of analysis. The main problem with a hybrid method is obtaining structure inputs to the coarse math model. Finite-element methods, being a complete analysis, need validation by test."

DESCRIPTION OF NONLINEAR DYNAMICS COMPUTER PROGRAMS

Cronkhite, et al. describe some of the many computer programs which now exist:

> "Numerous simple-capability hybrid simulations are available (refs. 34 through 39, for example). Of these, the two most notable programs are those authored by Herridge of the Battelle, Columbus Labs and by Gatlin et al. of Dynamic Science, Inc. The work done by

Herridge and Mitchell was directed toward automobile crash impact, while that done by Gatlin, et al., examined the vertical impact of a helicopter fuselage. This latter program (called CRASH) simulates the fuselage as rigid masses connected by nonlinear axial and rotary springs in a predetermined arrangement. Both of these simulations are two-dimensional.

"Of the intermediate-capability programs, the most advanced and perhaps the most widely used hybrid simulation is KRASH by Wittlin and Gamon (refs. 40 and 41). KRASH utilizes a 3-D arbitrary framework of point masses connected by beams to simulate the fuselage structure. The remaining intermediate-capability programs use finite-element computer codes and include Shieh's work (ref. 42), CRASH by Young (refs. 43 and 44), and UMVCS by McIvor, et al. (ref. 45). Shieh idealizes the structure as a 2-D array of beams with yielding confined to the plastic hinges at their ends, while CRASH and UMVCS use 3-D models of a framework composed of rods and beams. UMVCS could also be considered a hybrid because it requires test data input to define the moment rotation curves for the plastic hinges at the beam ends."

"The detailed crash simulations are all 3-D finite-element codes with the capability of modeling stringers, beams, and structural surfaces such as skins and bulkhead panels. The four codes currently available are WHAM by Belytschko of Northwestern University (ref. 46), WRECKER by Welch, et al., of Illinois Institute of Technology (ref. 47), ACTION by Melosh, et al., of Virginia Polytechnic Institute of Technology and State University (ref. 48), and DYCAST by Pifko, et al., of Grumman Aerospace Corporation (ref. 49 and 50). WHAM currently can be used to idealize a structure which contains only isotropic material. It uses partly interactive yielding; i.e., the effect of shear stresses on plasticity is neglected. WRECKER contains the same formulations as WHAM but also has the added convenience features of graphics and restart. ACTION also has partly interactive yielding, and it can be used only with a structure constructed with isotropic materials. Additionally, ACTION also contains an internally varied time step with numerical error controls. DYCAST can idealize a structure constructed of orthotropic material. Its features include fully interactive yielding, internally varied time steps with error control, restart, and graphic output."

A summary of the assessment of these specific crash simulations is given in table 5.2 (from Cronkhite et al., ref. 33). Note that the hybrid codes do not account for collapse or failure under combined loads because the crash data inputs are derived from tests with a single load. All of the finite-element codes except Shieh's can account for multiple-load components. The crush test can furnish the hybrid computer codes with data to analyze orthotropic laminates and core-sandwich panels, while only DYCAST of the finite-element codes can analyze an orthotropic material.

None of the evaluated finite-element codes can currently analyze a core sandwich. WRECKER is the only one of these codes which will account for strain rate effects in a logical way by determining the local strain rate and adjusting the stiffnesses. All the hybrids can account for joint failure and crippling because these effects are part of the crush test data.

The program ADINA (ref. 51) has capabilities similar to DYCAST and will also be considered.

DESIRABLE ATTRIBUTES IN CRASH SIMULATION COMPUTER PROGRAMS

Three basic attributes are considered in evaluation of crash-simulation computer programs—technical capability, "permanence," and ease of use.

The most obvious attribute needed by a crash dynamics program is technical capability — the

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Table 5.2–Computer Crash Simulations Assessment

Item	Hybrid	Finite Element
Plastic collapse and crush	All	All
with combined loads	None	All except Shieh's
Material failure	All	None
with combined loads	None	None
Skin & bulkhead	All (Poorly)	WRECKER, WHAM, ACTION, DYCAST
Anisotropic lamines with	All	DYCAST
cored sandwiches	All	None
Beam cross-section deform. (crippling)	All	None
Joint deform. & failure	All	None
Strain rate stiffening	Kamal Herridge	WRECKER
With local variations	None	WRECKER

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program should be capable of modeling both elastic and plastic material behavior, and also be able to handle large structural deformation including buckling.

The ability to simulate impact in a general way is also very desirable. A general interference model would permit investigation of phenomena such as plowing, in which changes in the aircraft geometry during impact can modify the characteristics of contact between the aircraft and ground which in turn can change the sliding resistance of the ground. In the models investigated herein, contact can be modeled only if the general behavior of the contact is known in advance, i.e. parts of the structural model which contact and direction of contact.

Lack of a general purpose contact model in crash simulation codes investigated herein could be a serious drawback.

From the standpoint of a user, the permanence of a code is important. Permanence means that someone with a vested interest is looking after the code so that someone is available to answer questions and also some assurance that the code will not soon become obsolete through neglect of theoretical advances (which are happening rapidly in the field of computer simulation of structural dynamics).

Almost as important as the theoretical analysis capability of a program is its ease of use. Important features in this category include:

1. Thorough checking of input data for errors, and well designed error messages which pinpoint the error, help the user understand what is wrong, and (when appropriate) indicate probable corrective action. For example,

    "Error—Singular Jacobian" is a very unenlightening error message.

    "Error—element 27 is badly distorted. Check sequence in which nodes are specified" is much more useful.

2. "Grace under fire" — From time to time it is almost inevitable that a computer program will encounter a situation in which the computation cannot proceed. This can occur through errors in the input data which are so subtle or difficult to detect that normal error checking of the input data misses them, or through limitations in the theory on which the analysis depends. It is important that the computer program recognize this situation when it occurs and print enough diagnostic information that the user can figure out what went wrong. If the program stops in the middle of the computation without providing good diagnostic information, the user can waste days tracking down (often by trial and error) the error.

3. Well organized display of computed data. The output must be legible and complete.

4. Availability of graphics aids. In finite-element programs, the large volume of data needed to describe the structure and the (larger) volume of information computed for the structural analysis make automatic plotting of both the input data (i.e. the nodes and elements) and the computed data (e.g. time history information) mandatory if a program is to be used as an engineering tool.

Ease of use is usually not considered in evaluations of crash simulation programs, probably due to the evaluations being made by (or in close coordination with) the program developers rather than by a disinterested party.

Program efficiency has been deliberately excluded from consideration. A meaningful definition of efficiency is nearly impossible to obtain. The cost of running a problem is not a good measure since it depends not only on the computer used, but also on the method by which computation costs are reckoned at the particular installation. Moreover, advances in computer design continually reduce computation cost and also change the relative importance of use of different resources (e.g. central, processor time, disc access, etc.) Error checking, considered to be highly cost effective, would be inefficient by this measure since it would increase computation cost of a particular run.

COMPARISON OF KRASH, DYCAST, AND ADINA

Three computer programs were selected for review. KRASH and DYCAST were selected based on the recommendations of Cronkhite et al.:

"The major conclusions of this investigation on computer crash simulations for advanced material applications are:

1. There is no satisfactory single existing code

2. Hybrid codes are theoretically incomplete

3. Finite-element codes currently lack sufficient advanced material capability

"The recommendation for current crash simulations on advanced materials is to use KRASH with applicable crush test data for preliminary parametric studies and gross evaluations. For a detail design, DYCAST can be used for analyzing orthotropic laminates. However, this code is still under development and has not yet been experimentally verified. It is not currently possible to perform an extensive detailed design evaluation of a structure with sandwich-core construction. This type of construction holds promise for increased energy dissipation with advanced composites."

The computer program ADINA (Automatic Dynamic Incremental Nonlinear Analysis) was selected, based on in-house experience with the code of the analysis of cracking/crushing for concrete structures under large, transient loads. Features of the three codes are summarized in table 5.3.

KRASH

In their review of KRASH, Cronkhite, et al. reported:

1. "The KRASH analysis was found to be a useful tool for studying effects of various impact conditions and parameter variations on the overall crash-impact response of the airframe, whether the airframe is of metal or composite construction.

2. "There is excellent documentation and correlation of the KRASH program (refs. 52–55). These documents should be useful to anyone working in the area of structure crashworthiness and simulation whether or not the KRASH program itself is used."

"KRASH has many useful built-in crashworthiness features, such as:

• Energy summaries

• Occupiable volume change and penetration

Table 5.3–Comparison of Program Input Features

Characteristic Types (note 1)	KRASH	DYCAST	ADINA
Element Types (T)	TRUSS BEAM rigid links	TRUSS BEAM 3-D membranes 3-D solid Core-Sandwich plate	TRUSS BEAM 2-D plane stress, plane strain 3-D membrane (plane stress 2-D Axisymmetric shell or solid 3-D solid thick shell Thin shell 2-D fluid 3-D fluid
Material Model	Curve	linear orthotropic elastic-plastic	linear orthotropic elastic, non-linear elastic, thermo-elastic elastic plastic (Von Mises or Drucker-Prager yield, thermo-elastic-plastic-creep (Von Mises yield), Mooney-Rivlin Material, concrete model, user defined Isotropic or Kinematic hardening.
Mass Model (T)	Lumped	Lumped or consistent	Lumped or consistent
Geometric Nonlinearity (T)	yes	yes	yes

Table 5.3–Comparison of Program Input Features (Concluded)

Characteristic Types (note 1)	KRASH	DYCAST	ADINA
Integration Method (T)	Euler predictor-corrector fixed time	Newmark, Wilson, Central Difference Modified Adam variable time step (except central difference)	Newmark, Wilson, Central Difference, all fixed step/predictor-corrector/time step
Plot capability time history of displacements, velocities accelerations (U)	no	yes	no (note 2)
Deformed Structures (U)	no	yes	no
Special Crash Output energy distribution Structural c.g. computes occupiable volume (U)	yes yes yes	yes no no	no no no
Documentations Theory manual (U) User manual (U)	Complete Complete	not available on single document preliminary	complete complete
Size of user community (U)	small	very small	large

Notes:
(1) The symbols (T), (U) and (P) used in the characteristic column indicate the type of feature; T refers to Technical capacity, U refers to user convenience, and P referrs to "permance" - the likelihood that the program will be maintained.

(2) Plot capability for ADINA is being developed by ADINA's authors.

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- Automatic rupture of elements

- DRI and man model

- Friction and plowing

- Soil

- Sloped surface impact

"Because of the coarse mathematical representation of the structure, the major problem with performing a KRASH analysis is involved in the 'art' of modeling and obtaining structure inputs to the program."

Cronkhite, et al. found a number of errors in the KRASH code and weaknesses in the analysis, as well as an inconvenient input scheme, some FORTRAN coding errors that were discovered are the following:

1. "The printer plot routine contained array dimensioning errors that occurred randomly when plotting element loads and relative deflections.

2. "No input for external crushing springs caused all material properties to be zeroed out.

3. "Maximum external spring load after bottoming out was internally set to ten times the load just prior to bottoming out which in some cases did not slow the vehicle down. This has since been fixed by making the cutoff load ten times the maximum load used before bottoming out.

4. "The damping coefficient for beam elements remains a constant value even through the element stiffness has been reduced by the stiffness reduction factor KR. The damping should also be reduced by the same factor as the stiffness."

"For engineers accustomed to user-oriented structural analysis digital computer codes, such as NASTRAN, the input to KRASH seems cumbersome. A preprocessor to help convert NASTRAN input data to KRASH input may partially solve this problem. This would also facilitate user training on the KRASH program."

Cronkhite et al. recommended a number of corrections/improvements be made to KRASH,

1. "Because the airframe structure often fails locally at a weak spot, a plastic hinge element for the internal structure modeling is needed. Also, scalar springs would be useful for modeling seats and main rotor pylons.

2. "The user should be allowed to apply arbitrary boundary conditions to the model.

3. "A 12 by 12 direct input matrix option would essentially allow substructuring.

4. "KRASH now uses a fixed-time step integrator. A variable time step procedure should be employed to improve run times. Also, an implicit integrator such as the Newmark-Beta method should reduce run times as well as improve numerical stability.

5. "A rigid body motion analysis for impact such as rollover where no significant structure response occurs for long periods of time would greatly reduce solution times.

6. "Damping should be added to the external springs.

7. "The stiffness reduction features (KR) should apply to element damping as well as stiffness.

8. "Input improvements

- Add descriptive names to identify data types

- Allow arbitrary mass point numbering by user

- Develop a NASTRAN to KRASH input preprocessor

9. "Add structure plotting capability — deformed and underformed."

DYCAST

Cronkhite, et al. reported: "This demonstration of DYCAST as a crashworthiness design analysis tool pointed out its usefulness while indicating some need for improvement. The main items in this assessment are:

1. "Gross dynamic behavior was displayed, including overall structural deformation and motions of critical masses.

2. "Detailed dynamic response was shown in the deformations, strains, stresses, and loads on individual structure components for metals and orthotropic composites.

3. "Detailed structural modifications were indicated by noting overloaded components and equipment attachment points and showing action of the energy absorbers.

4. "Computational costs were acceptably moderate, using 1.9 CPU minutes per problem-time msec for 471 degrees of freedom, while the restart feature permitted small time segments to be run in sequence without tying up the computer.

5. "Immediate improvements needed are rebound from the barrier surface and automatic failure criteria, which are now being implemented.

6. "Future developments needed are the addition of a core-sandwich plate element (for honeycomb and other cored structural components), output of occupant decelerative injury parameters, and calculation of energy consumption and distribution.

7. "Test verification is a very important need to explore the range of applicability and accuracy."

It is significant that Cronkhite is apparently satisfied with the DYCAST input scheme and does not report any analysis or coding errors. Some of the recommended improvements have since been made.

ADINA

The ADINA program has been developed by Dr. Bathe at the Massachusetts Institute of Technology (ref. 51). There is an active user group which holds regular conferences regarding ADINA engineering applications. ADINA has dynamic-analysis capability roughly equivalent to

DYCAST, but in addition has static-analysis capability (linear or nonlinear) and can perform eigen value/eigen vector calculations. A noteworthy feature of ADINA is the extensive checking of the input data for errors and the relatively complete set of error messages flagging errors which develop during execution, for example, singularity of the stiffness matrix. The major deficiencies are the input scheme, which is "fixed field" and relatively difficult to locate individual data items : i, and the lack of a variable time step numerical integration scheme.

Existance of an active ADINA user group is a significant asset, and a user without continuous need for nonlinear dynamic analysis should give ADINA serious consideration based on this alone. Existence of the user group assures that assistance will be available to extend or recheck an analysis at a later date.

SUMMARY

There is agreement between researchers in crash dynamics that both the hybrid approach and the purely mathematical finite-element method are needed at the current level of technology. Cronkhite, et al. note the inconvenience of coping with multiple input schemes.

Since the hybrid and purely mathematical finite-element analysis methods are compatible and, in fact, very similar, consideration should be given to developing a single package combining the best features of both approaches. There are two advantages. First, the user, who will likely need both methods to solve his problem, will need to become familiar with just one program. Secondly, combined analysis becomes possible; a detailed finite-element model can be used for one part of the structure (e.g. a seat) while another portion of the structure could be modeled more simply with hybrid elements whose static mechanical properties are obtained by static test. In principle, the static test could be simulated by the purely mathematical code; in practice, more validation of the purely mathematical codes is needed before this is practical.

A deficiency in all these models is the lack of a general purpose contact element to model collision between two or more parts of the structure. In existing programs, contact can be modeled only by connecting elements, e.g. springs, between contacting surfaces. This entails anticipation of every collision which might occur and each individual specification of the contact element together with its mechanical characteristics. Reference 56 describes an experimental general purpose contact model, which might be developed into a practical contact element.

TEST TECHNOLOGY

A review of crash tests has been conducted to ascertain the status of test technology. Tests include full-scale aircraft and some components. Test objectives, instrumentation, and test methods are discussed. In addition, some static tests applicable to structural crashworthiness are reviewed.

Programs to test full-scale aircraft have been conducted by NASA, the FAA, and the U.S. Army over the last 30 years. These programs have treated small propeller-driven transports, general aviation light aircraft, and helicopters. During this time, testing technology has advanced, particularly in the areas of instrumentation, data acquisition, and processing.

Seats, fuel cells, and landing gear have been tested statically and dynamically in development and certification testing to design crash loads. In addition, as a part of research programs some substructures have also been tested.

The purpose of crash testing has been to assess crashworthiness, level of crash loads, crash response of the aircraft, and crashworthiness performance of design modifications. More recently,

as analytical methods have evolved, some tests have also had the collection of data for verification of analyses as an objective.

In the material presented below, selected tests are presented as representative of r. technique. The test methods in some cases have been quoted from the reports and in other cases have been summarized.

FULL-SCALE PROPELLER-DRIVEN TRANSPORTS (Test Track Method)

Early crash tests by NACA of full-scale World War II vintage propeller-driven aircraft (refs. 57 and 58) had determination of crash loads and effects of crash parameters on these loads as an objective. These tests were part of a crash-fire study and utilized the test facility developed for that program.

Aircraft were propelled along a track, gear sheared off, and then impacted a shaped earthen barrier to simulate impacting the earth. Angles of impact up to 30° at speeds of about 100 mph were obtained. Floor accelerations at various stations along the fuselage were measured. In general, the aircraft impacted the shaped barrier in the vicinity of the cockpit. This type of test is representative of a flight into obstruction where the obstruction is an earthen mound. Some tests were performed to simulate the effect of hitting trees with one wing to produce a ground loop.

Acceleration data were obtained with instrumentation and processing equipment representative of the late 1950s. Due to differences in aircraft structure, crash energy levels, absence of analytical tools, and to the small amount of data on the crash performance, the test data have limited application to commercial jet transport. However, the data are of historical value and do provide some insight into crash loads. Further they served as models for later testing.

In 1964, the FAA conducted two crash tests of complete aircraft. A Lockheed L-1649 (ref. 59) transport aircraft and a Douglas DC-7 (ref. 60) were tested using methods similar to the NACA tests. In these tests, instrumented seat installations and dummies with seat restraints were included. In addition, high-speed camera coverage of the aircraft interiors was provided. Floor and dummy accelerations were measured.

Instrumentation problems due to test equipment acceleration environment on the DC-7 resulted in the loss of much of the acceleration data for that test. In addition, the DC-7 almost overran the test range, illustrating problems of controlling the test vehicle during crash impacts.

While these tests provided some good crash loads data, particularly for the seat/occupant, the value of the test data would have been enhanced by the availability and application of analytical methods to the data. Lack of such methods has limited the application of the crash loads to the test conditions for the type of aircraft.

FULL-SCALE CRASH TESTING OF GENERAL AVIATION AIRCRAFT (Swing Test Method)

Full-scale crash testing is performed at the Langley Impact Dynamics Research Facility (refs. 61 and 62). This facility is the former Lunar Landing Research Facility modified for free-flight crash testing of full-scale aircraft structures and structural components under controlled test conditions. The basic gantry structure is 73 m (240 ft) high and 122 m (400 ft) long supported by three sets of inclined legs spread 81 m (267 ft) apart at the ground and 20 m (67 ft) apart at the 66 m (218 ft) level. A movable bridge with a pullback winch for raising the test specimen spans the top and transverses the length of the gantry.

Test Method

The aircraft is suspended from the top of the gantry by two swing cables and is drawn back above the impact surface by a pullback cable. An umbilical cable used for data acquisition is also suspended from the top of the gantry and connects to the top of the aircraft. The test sequence is initiated when the aircraft is released from the pullback cable, permitting the aircraft to swing pendulum style into the impact surface. The swing cables are separated from the aircraft by pyrotechnics just prior to impact, freeing the aircraft from restraint. The umbilical cable remains attached to the aircraft for data acquisition, but it also separates by pyrotechnics before it becomes taut during skid-out. The separation point is held relatively fixed near the impact surface, and the flight path angle is adjusted from 0° to 60° by changing the length of the swing cable. The height of the aircraft above the impact surface at release determines the impact velocity which can be varied 0 to 26.8 m/s (60 mph). The movable bridge allows the pullback point to be positioned along the gantry to insure that the pullback cables pass through the center of gravity and act at 90° to the swing cables.

To obtain flight path velocities in excess of 26.8 m/s (60 mph) a velocity augmentation method has been devised which uses wing-mounted rockets to accelerate the test specimen on its downward swing. Two Falcon rockets are mounted at each engine nacelle location and provide a total thrust of 77,850 Newtons.

Instrumentation

Data acquisition from full-scale crash tests is accomplished with extensive photographic coverage, both interior and exterior to the aircraft, using low-, medium-, and high-speed cameras and with on-board strain gages and accelerometers. Strain gage type accelerometers (range of 250 and 750 g and 0 to 2000 Hz) are the primary data generating instruments, and are positioned in the fuselage to measure accelerations both in the normal and longitudinal directions to the aircraft axis. Instrumented anthropomorphic dummies (National Highway Traffic Safety Administration Hybrid II) are on board all full-scale aircraft tests conducted at Langley. Restraint system arrangement and type of restraint used vary from test to test.

Data signals are transmitted from the aircraft specimen through an umbilical cable to a junction box on top of the gantry. From the junction box, the data is transmitted through hard wire to the control room where the data signals are recorded on FM multiplex recorders. In order to correlate data signals on the multiplex recorders with external high speed motion picture data, an IRIG A time code was recorded simultaneously on the magnetic tapes and on films. There is also a 60 Hz time-code generator with the onboard events recorded with the cameras. A Doppler radar unit is placed approximately 60 m behind the impact point to obtain the horizontal velocity of the aircraft.

At the time the data is being recorded, the data passes through a 600 Hz low-pass filter. The data on the magnetic tapes are then digitized at 4000 samples per second. Digitized accelerometer data is then passed through a finite impulse response filter and filtered as follows:

1. Dummy head   600 Hz (unfiltered)

2. Dummy chest   180 Hz

3. Dummy pelvis   180 Hz

4. Seat   20 Hz

5. Floor structure   20 Hz

Motion picture analysis consists of plotting a displacement-time curve from the film data and fitting least square polynominal functions (up to tenth order) to the measured displacements and then twice differentiating the displacements to obtain accelerations. Accelerations thus obtained compare very well with the filtered accelerations.

COMPONENT TESTS USING CATAPULT METHOD

These tests (ref. 63) are not designed to bring the cabin environment up to the limits of survivability, but they are designed to expose the fuel tank location to a destructive environment.

Crash tests were performed at the National Aviation Facilities Experimental Center (NAFEC) catapult facility. A compressed-air catapult was used to accelerate the test aircraft along a 90-foot track. At the end of the catapult stroke, the aircraft, which was pulled by its nose gear, was released to impact an earthen hill of 4° slope. At the base of the hill, a 12-in. by 12-in. I-beam was installed to break off the aircraft's landing gear. The nose gear was strengthened to withstand the catapult pulling force, while the main landing gear mounting bolts were sawed in half to effect an easier separation from the wings. Spoilers were installed along the upper wing surface to keep the airplane from flying. At a distance of 10 ft from the I-beam, poles were sunk into the hill to a depth of 18 inches. These poles were spaced symmetrically off the centerline of the hill, at 42 inches and 108 inches each. The poles were hollow mild steel tubing, 4.375-in. outside diameter, 0.188-in. wall thickness and were 10 ft in length. Small rock piles were located on the hill to further increase the severity of the crash condition. There are no standards in general use for a crash site as is used in this type of test; hence, the selection of the type of poles, rocks, and hill were selected to produce a destructive environment to the fuel tank location. The crash site was intended to be at least as severe as a crash at an airfield involving airport structures such as approach lights.

In all tests, the aircraft main tanks were filled with water. Accelerometers, CEC type 4-203-001, were installed on the floor of the aircraft at the longitudinal center of gravity location (station 126). Accelerations in the vertical and longitudinal direction were recorded on an oscillograph. The data were filtered at 90 Hz.

DYNAMIC SEAT TESTS (Sled Test Method)

The testing of seats to simulate dynamic crash loads has been conducted by the U.S. Army, CAMI, NADC, NASA, and the seat manufacturers. The Army, following the recommendations of its Aircraft Crash Survival Design Guide, has had helicopter and light aircraft seats dynamically tested as a requirement for specification compliance. These tests have been conducted at the CAMI facility or by Simula, Inc. These test programs have served as development tools in uncovering unanticipated weaknesses in design details and generally have resulted in an improved crashworthy seat for the Army application. The Army test requirements include provisions for applying the test impulse with the floor in a pre-warped position. While these conditions may represent limiting cases for the Army usage, the heavier commercial jet aircraft construction may preclude warping to the degree required by the Army.

The CAMI facility (ref. 64) uses a sled test vehicle on a horizontal track to carry the seat and occupant (anthropomorphic dummy). The sled is gradually accelerated to a velocity and is abruptly decelerated by energy absorbing wires to apply the test impulse. Variation in orientation in mounting of seats permits loading in the desired axis. This procedure has been refined and generally gives good test results.

Test Procedure

Two impact orientations were used in these tests. The first, corresponding to Test 1 of

MIL-S-58095 (AV) (ref. 65), produced combined downward, forward and lateral loads on the seat. The second provides forward and lateral loads on the seat and corresponds to Test 2 of MIL-S-58095 (AV). Both tests used a floor warpage fixture which rolled the left seat track 10° outboard and pitched the right seat track 10° down, corresponding to the floor buckling and warping conditions required for static tests under MIL-S-58095 (AV). An Alderson CG-95 anthropomorphic dummy, S/N 500, weighing 224 lbs furnished for these tests by the Naval Air Development Center (NADC), simulated the seat occupant. The dummy was clothed in acrylic knit pants and shirt for these tests. Shoes were not used. Triaxial clusters of accelerometers were located in the dummy's chest, on the seat pan, and on the floor fixture. Strap load tensiometers were placed on the shoulder belt and lap belt webbing. Because of the design of the restraint system, there was no free webbing on which to locate the tensiometers, so that each tensiometer was in contact with the dummy as well as the webbing. Since this may introduce error in the data, the webbing load data presented in this report should be used with caution. An accelerometer was also mounted on the sled to provide reference data for adjusting the impact pulse. Unless otherwise noted, sled and floor data were filtered in accordance with Channel Class 60 (0-100 Hz) seat and dummy accelerometers in accordance with Channel Class 180 (0-300 Hz) and tensiometers in accordance with Channel Class 600 (0-1000 Hz) of SAE J 211b.

All tests were filmed on instrumentation cameras operating at 500 or 1000 frames per second.

TEST/SIMULATION PROGRAM OF STRUCTURAL COMPONENTS (Drop Tower Method)

This program (ref. 66) called for crash testing and analytical simulation of helicopter structural components and correlation of the results.

The primary objective of this activity was to provide a validation of the analytical techniques for helicopter crashworthiness design developed to date and as improved in this program. There was also an interest in gathering basic crash response data that could be used directly in design or as input to analytical procedures.

A nose section of a CH-47 helicopter from station 160 forward was used as the basic structure. A forward transmission and rotor head assembly were installed. Two crew seats were installed in the cockpit; a standard CH-47 seat at the pilot location and a crashworthy crew seat at the co-pilot station. Each seat contained a dummy which approximated the 50th percentile aviator. Total weight of the specimen complete with seats and dummies was 3800 pounds.

Instrumentation

Types of measuring devices used in this test were accelerometers, strain gages, and deflection indicators.

In addition to ±100 g accelerometers some ±500 g shock accelerometers were used in areas where high acceleration levels were predicted. These were used to overcome previous problems where high g levels caused circuit saturation resulting in excessive zero shifts with long-term decay characteristics.

Five ±100 g accelerometers (CEC 4-281-001) and five ±50 g accelerometers (PCB Piezotronics Inc., Model 302A) were mounted at selected locations. Three deflection indicators were mounted at selected locations. Indicator tubes were attached to the floor and passed through the roof of the specimen. Eight strain gages were installed on selected structural elements. All gages were unaxial. An additional strain gage was installed on the crashworthy crew seat vertical colunmn. All data were recorded on magnetic tape using an FM wide-band IRIG recording system.

Hoisting equipment was adjusted prior to the test to provide a nominal pitch attitude at release of 0° and a drop height of 17.3 ft to give an impact velocity of 33.3 ft/s. Roll and pitch attitudes were also set to 0°. Four ropes were attached to the specimen to limit to 45° any postcrash rotation about the pitch and roll axes.

Black and white movies (1500 pps) were recorded at three locations and provided three views: a rear view of the specimen, an oblique view from the right rear and another oblique view from the left front.

A 400 pps color movie camera was set to view the crashworthy crew seat through the left side copilot door opening of the cockpit. Additionally, two 24-pps movies were taken at approximately the same locations as the two 1500-pps cameras positioned obliquely to the specimen.

Of the 10 accelerometers used, all provided good data for the inital impact phase of the test. Subsequent to initial impact, at time 0.06 second, one accelerometer signal was lost due to collapsing structure of the station 95 bulkhead pinching a wire between the structure and the edge of the mounting plate for the crashworthy crew seat. This resulted in signal loss from the accelerometer mounted on the crashworthy seat-mounting plate. However, the data obtained up to the time of signal loss is acceptable and covers the major range of interest for a test of this type.

Three deflection indicators were mounted in the test specimen. These were to provide time-history records of the displacement of the specimen's crown relative to the floor, and also to give a post-test indication of the plastic deformation that occurred.

By using the pretest dimensions of the specimen in conjunction with the post-test gross deflection indications provided by a rubber grommet sliding on each indicator tube, it is possible to determine the maximum elastic and plastic deformations that occurred during the crash sequence.

Unfortunately, only one of the deflection indicators provided acceptable deflection time-history data; the other two suffered from poor wiper contact and possible wire binding and stretching.

A total of nine uniaxial gages were installed, eight at selected locations on the structure and one on the vertical attenuator of the crashworthy crew seat. Some of the gages were in areas where severe structural damage occurred resulting in gage failures, zero shifts, and generally unacceptable data.

The strain gage acceptability limitation is the manufacturer's recommended 1.5% strain value for room temperature conditions.

Test Conclusions

This test provided reasonably good initial impact data for all accelerometer channels without obviously extreme zero shifts or early loss of signal. The modified circuitry and use of 500 g accelerometers for recording impacts of this magnitude shows a marked improvement over the results obtained for test numbers 1 and 2.

The selected impact velocity provided sufficient energy to cause failures of many of the structural elements without causing excessive collapse. It is apparent that a greater impact velocity would have resulted in excessive structural collapse and rendered the test unrepresentative of a survivable crash.

The strain gages suffered from the effects of adjacent structural failures rendering the data of questionable value in some instances. In fact, it is proving to be extremely difficult to select positions for the strain gages where useful data is obtained and adjacent structural failure does not occur.

In a test where limited instrumentation capability exists, it is considered that the use of more accelerometers and less strain gages may prove to be more cost effective in providing data suitable for correlation with analytical results.

The deflection indicators again did not perform well, with only one providing a deflection time-history. It appears that the problem is due to poor wiper action in conjunction with stretching wire; future tests will incorporate a stronger wire material such as piano wire. Such an installation will possess a lower electrical resistance value but it is considered that an adequate recording system exists to accommodate this. Additionally, the generation of a continuous signal without wipe chatter will enhance signal recording.

It was unfortunate that the high speed movie films were spoiled in development since a better understanding of failure sequences may have been obtained for the primary structural elements.

However, overall structural damage and recorded data provide a good set of information for correlation with computer simulation results.

STATIC TESTS

Static tests provide useful data on the crash performance of structures where the inertia loads due to the local structural mass have a small effect on the crash response. Some examples of this are fuselage structures in shear action, lower fuselage structure in crashing action, and seat structure under floor displacement and occupant loads. The inelastic load carrying capability of skin-stringer, columns, and torque box sections for large deflections may also be obtained from static tests. These data are useful in hybrid simulations in validating detailed structural models, and in assessing design performance of some components.

Static tests, while avoiding problems of dynamic data acquisition, do have problems of maintaining load magnitude and direction, and valid boundary conditions during large deflections. Internal loads usually cannot be obtained by strain gages as strain gages fail at the large deflections of interest. However rapidly recording load cells and deflection gages may yield valid force-deflection curves for the loading condition.

These techniques have been used successfully in the Army-sponsored study and in the NASA General Aviation research on floor structure. Some further development of the methods might be expected as additional testing is performed.

IMPACT TEST FACILITIES

Impact test facilities suitable for research and development crashworthiness testing of structural subsystems and of complete aircraft have been reviewed. The review is confined to representative major government facilities.

Crash testing of commercial jet transports, or even structural components involves engineering problems of scale which have been overcome in past testing but now take on a new dimension. For the 707 the fuel load weighs 72,498.2 kg, the wing tip-to-tip span is 44.42 m, and the ground to fin tip distance is 12.94 m. Extension of past test methods to the commercial jet will require ingenuity.

Table 5.4 identifies the test facilities and shows approximate test capabilities. Regarding existing facilities, full-scale testing of commercial jet transport aircraft may be conducted at Dryden Research Center. The FAA Technical Center improved catapult will have the capability to test small jet transports like the 737, DC-9, and the F-28.

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Table 5.4—Impact Test Facilities

AGENCY	FACILITY	WEIGHT POUNDS	SIZE	VERTICAL VELOCITY FT/SEC	HORIZONTAL VELOCITY FT/SEC	DATA	COMMENT
NASA LaRC	Impact Dynamics Research	30000	?	72	72*	Good	*May be increased with rocket thrust
	Impact Drop Tower	15000	12'x20'D	56	?	Good	Under construction
	Landing Loads Track	20000	?	NA	186	Good	To be increased to 372 ft/sec
Dryden	Flight Crash Test Range	NA	NA	NA	NA	?	Complete aircraft remotely piloted
FAA Tech. Ctr.	Catapult (Small)	10000	?	NA	169	?	
	Catapult (improved)	200000	?	NA	287.3	?	Under consideration
	Impact Drop Tower	35000	?	50	105	?	
	Impact Drop Tower	100000	?	90	?	?	
CAMI	Sled Seat Tester	NA	NA	NA	NA	Good	To be modified Energy limited

With regard to testing of substructures and components, NASA Langley, the FAA Technical Center, and CAMI facilities may be used. The CAMI facility is designed for testing seat/occupants.

An important part of test facilities is availability of adequate instrumentation and data acquisition equipment. At a minimum, the data system should be able to record accelerations of ± 750 g at frequencies of 600 Hz. At least 24 channels of this type data should be available. The current NASA practice of passing the data through a 600 Hz low-pass filter prior to recording may be restrictive for stiff substructures. Also high frame-rate (5000-10,000 pps) photographic coverage should be available. At least three cameras are needed to record the structural response. A system for accurately indexing the photographic records to the electronic instrumentation is necessary.

ASSESSMENT OF TEST CAPABILITIES FOR JET TRANSPORTS

Based on the above discussions, assessments may be made of test capability, test method data, systems, and test facilities needed to conduct the research and development programs. The purpose of these test programs is to increase the knowledge of the crash response of the complete aircraft and components. In order to be effective, such testing must provide engineering results in much greater detail than that currently obtained from accident investigations.

Test Methods

Much research is required to develop test methods. With regard to testing of complete aircraft, the only carryover from previous testing is the L1649 and DC-7 tests, which apply to the ground to ground scenario. To test the air-to-ground and the flight-into-obstruction scenarios, remote piloting techniques to control crash conditions, and reliable onboard data acquisition techniques are required.

Regarding component testing, some carryover from previous testing pertains to the testing of seat/occupant/restraint systems. While methods of testing for individual seat units have been developed, there are many problems yet to be resolved. Of particular concern is the variation in results between what might be expected to be similar tests. Reference 65 shows a factor of approximately 2 in lap-belt loads that is attributed to the use of different types of dummies. The Army is concerned about this problem and is conducting a series of tests in which the same type of seat and identical dummy is tested to the same conditions at NARDC, CAMI and Simula, Inc. (ref. 67). The results of these tests are to be compared in an attempt to resolve the differences being observed.

In addition, the interface between seat track and support structure needs definition. For light aircraft and helicopters, deformations of one track relative to the other is usually recommended. For transport aircraft with deep floor beams, it is not clear that such relative deformation is obtainable or representative of crashes. In addition, the input acceleration pulse is yet to be determined. Such questions as how many seat units or how much floor structure are necessary to adequately simulate crash conditions are unanswered. Should load pulses be combined, phased, and/or applied in sequence? How do restraint systems perform under such conditions and what occupant should be represented?

Similar problems exist in testing each of the other components. In particular, how are crash loads to be reacted at the test-specimen boundaries in order to cause the structure to simulate the crash dynamics of an accident? For instance, how much fuselage must be tested in simulating the air-to-ground scenario? The ground-to-ground scenario? Are wing reactions necessary? Further, does the nature of the crash response change as a function of crash initial conditions?

To answer the kinds of questions present above, correlation between component testing and complete aircraft testing is necessary. Also, validated analytical methods are needed to extend test results to regions where testing is impractical and to correct results where crash boundary conditions cannot be matched.

Data Systems

Data acquisition and processing systems developed for the NASA/FAA general aviation program and the CAMI seat program are sufficient to start test programs. However further development of improved high g/high frequency accelerometers is needed. In addition reliable displacement measuring devices are needed for dynamic deflection and spring back measurements.

In the area of photography, methods of obtaining good quality high frame-rate (5000-10,000 pps) pictures in the crash environment are needed to record detailed structural behavior. Research into low-light-level television and methods of computerized picture enhancement and data extraction could greatly increase the data obtained and reduce data reduction time.

Test Facilities

Complete aircraft testing appears feasible at the Dryden Crash Test Range and at the planned FAA Technical Center catapult. Instrumentation at both facilities is open to question. At Dryden, onboard data systems are supplemented by telemetry used for flight tests. The telemetered data are of a low frequency and of dubious value. Technical Center catapult data system has not been defined to date.

The CAMI seat test range appears adequate for near term testing of individual seat units. Testing of larger groups of seats and substructure may require testing in other facilities. Other components might be tested in the assorted catapults, drop tower, and swing towers depending on the problems of simulating the crash.

ASSESSMENT OF IMPACT RESISTANCE TECHNOLOGY

Current impact resistance design technology is based on the lessons learned from accident experience. Technology is continually being improved to reflect the latest experience. From these lessons, experienced engineering design practices have evolved. These practices have developed a high level of impact resistance in the current commercial jet transport fleet.

The design technology has shortcomings in that most crash response mechanisms are unknown. There is a lack of quantitative methods for engineering analysis. There also is a lack of definitive crash loads. This has led to comparison of designs to existing capability. While this process has been successful where a data base exists, there is concern for new configurations and advanced materials application for which no accident data base exists.

Test methods for complete aircraft and for structural components need development. The most recent transport aircraft crash test was in 1964 with limited results. Jet transport structural component testing to simulate crash conditions needs development. Size and initial conditions of such testing introduces a new set of test problems. Adaptation of existing facilities and the development of new facilities needs research. Existing test facilities and methods could serve as a starting point for a test program.

Existing analytical methods are research tools. Many programs have technical shortcomings for crash simulation and are not completely validated, but if validated could contribute significantly

to test planning, prediction of results based on state-of-the-art knowledge and theory, and postcrash data analysis for complex interactions. Model techniques and structural data bases to support crash simulations for both structural components and complete aircraft needs development. Further, the programs need modification, both to make them user oriented before they can become engineering tools and to reduce the large cost of analyses.

For seat/occupant modeling the programs have reached a more advanced stage of development than the structures analysis programs. However, more complete representation of the occupant and surface contact would permit better simulation of occupant response. Problems exist in relating the analytical output to human injury.

As an overview, the problems have been defined and some analytical and experimental methods and facilities are available. It appears that the ingredients for research and development program exist. With the advent of advanced aircraft the impact response problems take on added significance.

RESEARCH TO IMPROVE CRASHWORTHINESS TECHNOLOGY

Requirements for research and development effort that will result in improved technology for crashworthiness engineering of commercial transport aircraft are presented. The required technology is discussed in terms of disciplines. Problem areas for current and advanced transport aircraft are identified, and areas of research and development are discussed.

REQUIREMENTS FOR IMPROVED TECHNOLOGY

Based on the assessment of the current state of technology four goals must be achieved to significantly improve crashworthiness engineering for commercial jet transport aircraft.

First, definition of the survivable crash environment is required. This definition should include crash loads and displacements for each scenario. Rational relationships between the crash loads and displacements and the range of initial conditions with various hostile environments should be established.

Second, an understanding of the crash response mechanisms of structural components and of complete aircraft in these scenarios is required. The effects of factors influencing these mechanisms must be understood.

Third, validated analytical modeling and test engineering methods must be developed. These methods should be capable of treating structural components, occupant response, and complete aircraft. Further the methods must be usable in engineering applications.

Fourth, human factors and injury mechanisms for commercial transport occupants must be defined. The relationships between engineering quantities such as acceleration pulses, impact loads and displacements, and occupant injury are necessary to provide adequate levels of occupant protection.

Achievement of these four goals will permit detailed engineering of crashworthiness to a level not now available. Improved technology will permit design considerations affecting crashworthiness to be treated on a more rational basis and to more fully participate in the design process. Further, as advanced design concepts and materials are considered, crashworthiness requirements may be more fully anticipated than in the past.

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CRASHWORTHINESS DISCIPLINE

"Mature" crashworthiness technology might be envisioned as five major areas of activity. Each of these areas leads to the quantification of crashworthiness parameters and understanding of crash phenomena in order that protection for occupants might be improved.

The five areas of activity are shown in figure 5.9. The areas are defined to the third level of detail. It is expected that technology will evolve as the program progresses.

DATA BASE

Data base activity treats the collection and maintenance of data germane to structural crashworthiness and occupant protection.

The data base has been divided roughly into four categories: crash statistics, scenario refinement, performance norms, and human factor data. For the most part, the activities under each of these categories are self evident and in many instances represent an extension of ongoing efforts and of studies conducted herein.

With respect to the establishment of survivable crash initial conditions, more applications of the work of Wingrove et al. (ref. 68) in conjunction with the NTSB could improve the definition of the crash conditions. Accurate definition of the initial conditions could enable accidents to be used in simulations to better define the environment in scenarios. Such results would augment the data from crash testing full scale aircraft.

To assist the NTSB in developing structural data for crashworthiness from accidents, an investigation team of research and engineering-oriented people from government is proposed. This team would inspect selected accidents to obtain data on the crash performance of structural systems. It is recognized that a high level of cooperation between the NTSB and the team must exist for such an endeavor. However, the increase in the amount of engineering data from accidents could be substantial.

Human factors area needs better definition. Considerable attention has been directed toward occupant injury mechanisms. However, with improved structural and occupant modeling, interactions between occupant and the restraint system and with the surroundings may be studied for improved design. Of particular importance is the development of a relationship between engineering parameters and occupant injury. Improved definitions of occupant modeling parameters such as spring constants, damping ratios, and kinematics should be developed for simulations and for anthropomorphic dummies.

METHODS AND FACILITIES

The methods and facilities area is concerned with development and validation of analytical and experimental methods, test facilities, and simulation techniques.

Current analytical programs such as KRASH, DYCAST, and MSOM-LA should be kept up to date and extended. Updating relates to modern program architecture to reduce consumption of computer resources and to facilitate user application. Further, with the advent of more powerful computers, existing codes should be rewritten to reflect these advances.

Extension of the analyses should more accurately depict the behavior of the structure. Occupant models should be extended to provide for 3-D response and for multiple occupants in a seat unit.
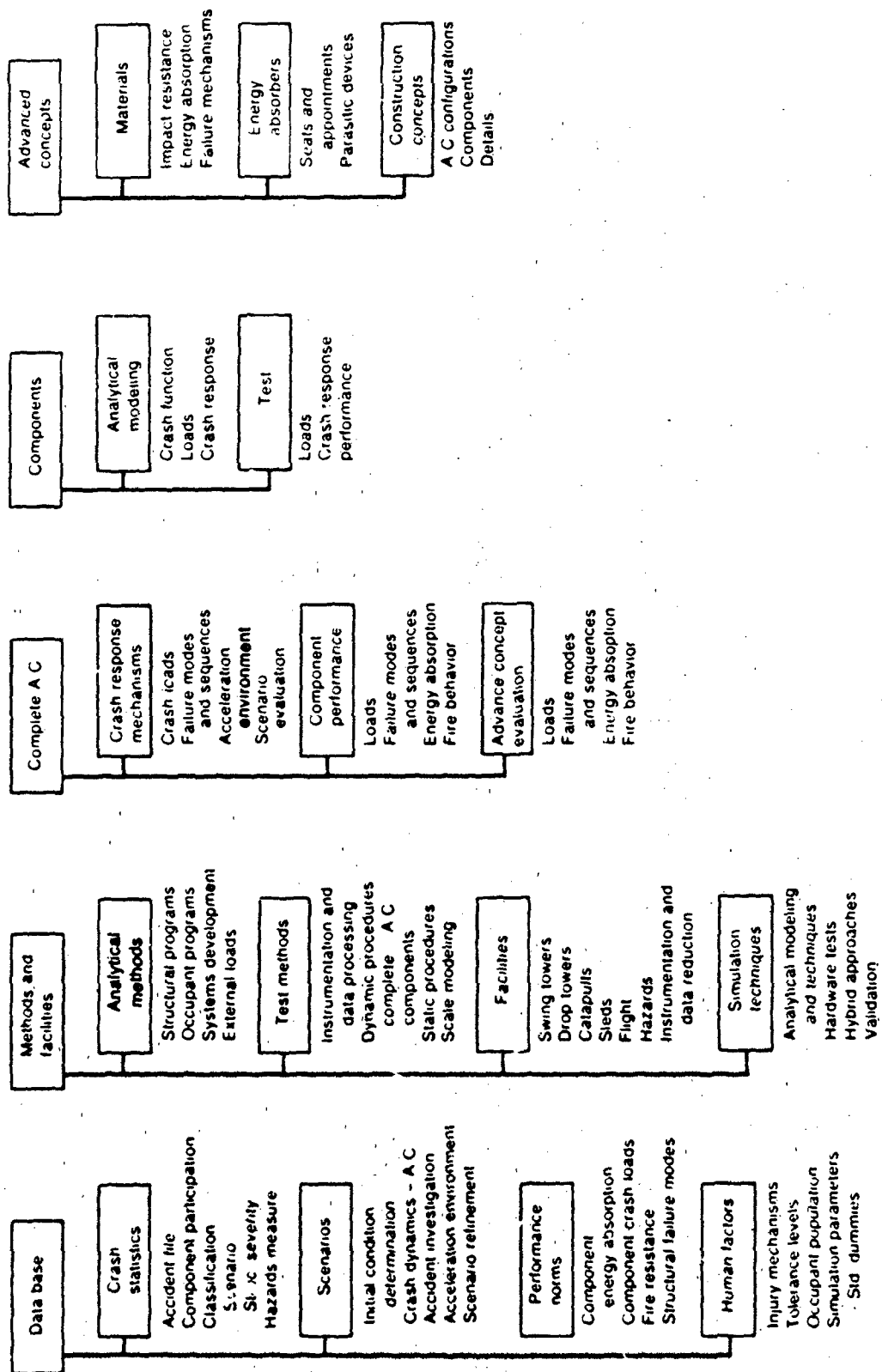
Figure 5.9–Crashworthiness Technology Research and Development Program

For instance, the inclusion of accurate modeling of seat structure and restraint harness in occupant models to depict the interaction between occupants and structure.

Structural programs should be extended to permit accurate representation of fluid pressures in fuel tanks under sudden accelerations for the tank rupture problem. Where multiple failure modes are possible, heuristic logic may be incorporated in the coding to permit the dynamic response to follow "minimum energy" paths. These types of approaches may even lead to using the computer to optimize the model while processing the data.

Development of modular analysis systems that permit the analyst to use only the modules necessary for the solution of problem at hand is needed. While it is desirable to enhance the capability of the analysis system, it should not be necessary to drag all these additional features into the computer for every problem. For instance, if one is analyzing floor structure only, then modules and storage for occupant response or hydrodynamic forces may not be needed. Efficient use of computer resources is a must.

Analytical methods and models for simulation of boundary conditions needs to be improved. Current programs introduce loads into the models through springs or through fixed boundaries. Accurate representation of this process is necessary if detailed simulated structural behavior is to be achieved.

The level of validation achieved for the analytical tools will affect the usefulness of the tools for engineering purposes. Hence, every effort is needed to improve fidelity of analytical results in simulating the crash response of structure. Experience and supporting data for modeling that will extend the applicability of analytical methods and develop confidence in engineering application are needed.

Crashworthiness test method research and development is separated into four areas: instrumentation and data processing, dynamic procedures, static procedures, and scale modeling. Effort in these areas is needed to improve current techniques to better represent crash conditions, to permit the study of structural subsystems, to acquire data for hybrid simulation, and to allow the use of scale models for testing large aircraft or components.

While a crash may have a duration of many seconds from initial impact to final arrestment, the critical deformation of structure may occur in milliseconds. This small time imposes severe sampling requirements on instrumentation. Current test data contains errors due to accelerometer drift, coordination of events, and to processing problems. Further, definition of actual response may be incomplete. Deflections should be dynamically measured to properly account for the sequence of failures and the effects of spring-back. In addition, the instrumentation must be sufficiently rugged to withstand the crash environment and still function properly.

Research and development is needed to improve the measurement of accelerations, velocities, and deflections under test conditions. The application of laser techniques should be investigated. Photography is particularly difficult and efforts to extend the coverage to high-frame rates is needed. Picture enhancement procedures developed for space exploration may have application.

Further effort is needed to handle the vast quantities of information obtained in a test and to present this information in a readily digestible format. This is particularly true of photographic data.

Dynamic test procedures may be separated into complete aircraft testing and structural subsystems tests. Methods of testing complete aircraft are complicated simply by the scale of the model. The up-coming test of the 720 aircraft in 1984 will suggest further areas for development.

Procedures for testing structural subsystems need further development. Current test methods for testing seats/occupant/restraints have provided good data. However, these methods are limited in model size, and in the crash pulse, which may be simulated. In addition, the construction and instrumentation of occupant models still raise many questions. In many respects, these problems are facility related.

Some testing of structural subsystems has been accomplished on fuel tanks and fuselage sections for small aircraft. These tests have been limited in direction of impact loads and in size of the test specimen. Extension of these methods to other subsystems and to a more complete range of load conditions requires effort. Further, the proper representation of structural boundary conditions and of external loads is needed.

Static test results have been found to be useful in obtaining input data for simulations involving some lightweight, highly stiff substructures. Methods for conducting these types of tests need development. In particular, methods of applying loads statically to simulate the dynamic load distribution are required. Further, a method of maintaining the applied loads and their directions through the large structural deflections is needed.

Scale modeling for crash tests to provide data at reduced costs and in a timely manner should be investigated. While scaling laws for crash testing are known, limitations on the method need be developed particularly with regard to model details and for orthotopic materials such as composites. Problems may exist with regard to ply thickness and fabrication methods for these materials.

FACILITIES

It is expected that as crashworthiness research and development progress, extension of existing facilities will be required. For some types of testing new facilities may be needed. A part of the total program is updating of existing facilities and development of new facilities.

As some facilities already exist in the FAA, NASA, the military, and industry, a team approach to facilities development should be used. An overview committee of interested parties should provide goals and policy for expansion and development of the necessary facilities.

SIMULATION TECHNIQUES

Methods of simulation need development. Methods of modeling to use analytical tools and of testing, to identify crash response, need to be developed to levels suitable for engineering application. Various approaches should be verified and validated. As better methods are developed, this information should be made available.

COMPLETE AIRCRAFT TESTING

Crash testing of complete highly instrumented aircraft is divided into three areas: identification of crash response mechanisms, structural subsystem performance, and advanced concept evaluation. Each of these areas is treated below.

Complete aircraft tests are required to identify the structural crash response mechanisms including the interaction of various subsystems. Included in this area are evaluation of crash loads, structural response, acceleration environment, and scenario definition.

Crash loads and acceleration environment will provide data for comparison with calculated values. These data, in conjunction with data derived from accidents, may be used to assess the adequacy of

crashworthiness for complete aircraft. Structural response will provide deflection, failure mode, and sequence data useful to the assessment of engineering methods such as simulation and modeling. Further, it may be used to evaluate and refine crash scenarios.

Structural subsystem crash performance may be obtained in the complete aircraft test. Loads experienced by the subsystems may be obtained for comparisons with design values and for use in subsystem testing. Failure modes and sequence may be obtained including effects of interaction with other subsystems. Energy absorption characteristics of the subsystem may be assessed and the adequacy of its crash performance may be assessed.

Complete aircraft tests should also be used to evaluate advanced crashworthiness concepts. For instance, applications of advanced materials or energy absorption designs for various subsystems may be assessed. Effects of such components on crash loads and environment may be evaluated.

As part of this testing, the contribution of the various subsystems in reducing the fire hazard and in protecting the occupants may be evaluated. Further, the full-scale crash tests afford opportunity to refine the definition and relate crash loads and displacements to scenarios.

STRUCTURAL SUBSYSTEMS

Research into the crash behavior of structural subsystems consists of both analysis and test. Emphasis is placed on treatment of subsystems because the subsystems must perform their crash function in order to achieve crashworthiness for complete aircraft. Further, it is in detailed mechanisms of failure that engineering changes may be affected. In addition, in testing the subsystem, detailed crash response of the subsystem may be better measured than from complete aircraft testing.

The potential for improved crash performance for structural systems has been assessed to provide some guidance for the planning of a research program. The potential for improved performance is assessed relative to the crash function. On this basis the assessment in table 5.5 is presented.

The rating potential for improved performance is given in relative terms; C being good potential, B being better, and A being best. These ratings are subjective and do not reflect the difficulty in advancing the technology. It is expected that some ratings will change as the research and development program progresses.

Analytical research treats the methods of modeling the subsystem to depict detailed crash response. Subsystems of immediate interest are wing tankage, seat/occupant, floor/seat/occupant, and fuselage sections. In this endeavor, the full power of analytical programs may be used to represent the structure in detail. Results of these analyses should be validated with subsystems tests. Computer programs may be assessed for technical deficiencies and simulation techniques may be developed for engineering application.

Testing of structural subsystems will permit identification of detailed failure mechanisms and sequences of events in simulated crash conditions. In addition, these results may serve as a basis for comparison for the evaluation of advanced concepts. In many instances, representative metal structure suitable for testing may be obtained from overaged transports being retired from service. Further, such structure specimens are within the test capacity of some existing facilities.

Advanced material applications for some subsystems may also be tested as a part of the metal specimens. As the applications advance, new specimens may have to be fabricated.

Table 5.5—Areas for R&D on Current Metal Aircraft

COMPONENT	Crash Function	Potential for Improved Performance	Areas for R&D	Comments
Landing Gear	Grd. Clearance	B	Terrain Tolerance	Reduce fuel spills due to grd. drag, lower surface tear; engine/pylon separation; lower fuselage crush; and fire hazard
Pylon/Engine	Clean Separation	C	Controlled Rupture of Support Structure	Reduce fuel spills due to tank tear and fire hazard
	Clean Separation	C	Controlled Rupture of Support Structure	Reduce fuel spill from tank tear and fire hazard
Wing Tankage	Contain Fuel	A	Fuel, Hydraulic, Electric Line Separation	Reduce fire hazard
			Improved Resistance to Rupture and Lower Surface Tear	Reduce fire hazard
Fuselage	Retain Integrity	B	Resistance to Breaks	
	Prevent Fire Entry	B	Prevention of Holes	
			Heat Rejection	Better occupant protection
	Flotation	B	Resistance to Breaks	
Lower	Energy Absorption	C	Increase Energy Absorption	Lower loads on occupants and cabin interior equipment
	Prevent Water Entry	B	Increased Plate Strength	Improve flotation and reduce floor displacement

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Table 5.5–Areas for R&D on Current Metal Aircraft (Concluded)

COMPONENT	Crash Function	Potential for Improved Performance	Areas for R&D	Comments
Upper	Protective Shell	C	Energy Absorption and Integrity	
	Energy Absorption	C		
Fuel Distribution System	Limit Fuel Spillage	B	Fuel Line Separation	Reduce fire hazard
Floor Structure	Energy Absorption	B	Energy Absorption	Reduce occupant loads
	Retain Seats and Interior Equipment	B	Controlled Deformation	Improve seat retention
	Provide Egress	C		Reduce door blockage
Seats/Restraint System	Occupant Constraint	C	Occupant Dynamic Response	Reduce occupant injury due to surface contact and to restraint loads
	Energy Absorption	C	Improved Energy Absorption	Reduce occupant loads
	Remain Attached to Floor Track	B	Seat/Floor Dynamic Response to Crash Accelerated Loads	Prevent ejection and contact with interior Acceleration environment requires definition
	Release as Required	C	Ease of Release	
Cabin Interior	Contents Containment	B	Dynamic Response	Reduce debris and occupant injury
	Structural Integrity	B	Structural Attachments	Reduce egress blockage
Entry and Escape Doors	Operate as Required	B	Effects of Fuselage Distortion on Operation	Reduce egress blockage

Subsystems should be tested over a range of initial conditions compatible with those used for complete aircraft.

ADVANCED CONCEPTS

Research and development for advanced crashworthiness concepts includes areas of new materials, energy absorbing applications, and a general category called "construction concepts." It is anticipated that as crashworthiness technology is developed and as new structures and materials technology is applied to aircraft design, advanced concepts may be necessary to provide occupant protection in crashes.

The new materials area is concerned with developing technology for understanding failure mechanisms, and for increasing impact resistance and energy absorption characteristics of these materials, principally composites. The effort treats materials at coupon or small specimen level, and deals with effects of hybrid materials, ply orientation, etc.

Fire resistance of advanced materials should be investigated in both small specimens and in structural components. Methods of improving burn characteristics should be evaluated. Structural performance of these components in the presence of crash heat pulse should be understood.

Energy-absorbing applications are concerned with seats and immediate occupant surroundings and with "parasitic" materials/devices introduced specifically to provide energy absorption. An example of the latter is crushable material applied at the underside of the fuselage to provide energy absorption.

Construction concepts are concerned with effects of application of the advanced materials to aircraft details and components on the crashworthiness of aircraft configurations. At this time, the crash response of aircraft primary structure made with new materials is unknown. It is conceivable that historic crash functions of the aircraft subsystems may have to be modified in this process and new strategies for protection of occupants devised.

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6.0 CONCLUSIONS AND RECOMMENDATIONS

One hundred and fifty-three jet transport accidents have been studied in depth. The status of structural crashworthiness technology has been reviewed. Conclusions resulting from these studies are presented and discussed. Based on these conclusions, problem areas relating to commercial transport are identified for future research and development. Finally, a research and development program is recommended.

When considering all the commercial air transportation system safety related problem areas it is believed that the most significant reduction in fatalities can be achieved by simply reducing the number of accidents. No significant technological breakthroughs are required to achieve this goal. In section 2, it was shown that approximately 76% of the commercial jet aircraft accidents have been attributed to cockpit crew factors. Therefore, research and study of these factors in areas of cockpit design, system design, and crew human factors should receive major emphasis.

Another safety-related problem area is the airport environment. Studies of ground traffic control systems and ground operation procedures should be directed toward elimination of collision accident. The severity of many veer-off and overrun accidents could be substantially reduced if hazards on and around the airport were eliminated.

Current commercial jet transport aircraft possess a high level of crashworthiness. This is due in part to stronger structure, less volatile fuel and improved design methods. Design methods are continually being improved based on knowledge gained from accident experience. It is desirable to continue this improvement of existing designs and to retain their beneficial characteristics as future designs using advanced materials and concepts are developed. To achieve this will require substantial advances in structural crashworthiness technology.

CONCLUSIONS OF THE STRUCTURAL CRASHWORTHINESS STUDY

First, the greatest potential for improved survivability in commercial jet transport aircraft accidents is in the area of fire related fatalities. Research relating to prevention of fuel fire merits the highest priority. Time is a critical element associated with escape when a severe fuel fire exists outside the aircraft or when the aircraft is sinking in deep water. If flame and smoke enter the fuselage passenger area immediately after the aircraft comes to rest, the probability of escape is reduced substantially. Retaining fuselage integrity and delaying entrance of smoke and flame is essential if survivability is to be enhanced. Debris and obstructions that hinder movement of persons on the escape route cause delays that reduce the probability of survival. Consequently, factors that would increase the available time for egress or reduce the time required for egress is essential. Fuel additives as in the anti-misting kerosene program, rupture resistant fuel tanks or cells, and structural improvements to protect fuel tanks and occupants should be subjects of research.

Second, structural integrity of fuel systems, fuselage, and landing gear are leading candidates for improved crashworthiness. Structural integrity of fuel systems is a key factor in prevention of postcrash fire. Integrity of the fuselage contributes to the reduction of fire related fatalities by preventing or delaying the entry of fuel, fire, and smoke and by maintaining egress routes. Main landing gear that are more tolerant to off-runway conditions would continue to provide ground clearance for the wing and engine pods thereby reducing wing breaks and tearing of tank lower surfaces, and engine pod scrubbing or separation.

Third, where trauma fatalities have predominated, the energy absorbing protective capability of the aircraft structure generally has been expended and the aircraft has experienced major structural

damage. This is discussed in section 5. However, trauma fatalities might be reduced by improving energy absorption capability and fuselage structural integrity. While current occupant seat/restraint systems have performed well in accidents, little is known of the relationship between occupant response and structural dynamic characteristics of the seat, floor, and fuselage. Only recently has modeling progressed to where some of this behavior can be more thoroughly explored. This becomes particularly important for applications of advanced materials. Further, aircraft occupant impact tolerance needs improved definition.

CRASHWORTHINESS PROBLEM AREAS

Based on these conclusions, problem areas for future structural crashworthiness research and development are presented. These problem areas are categorized with regard to current aircraft, advanced aircraft, and full-scale crash tests. Within each category problem areas are presented in order of priority. The problems are shown in figure 6.1.

Postcrash fire hazard reduction through the development of fuel additives, improved fire resistance technology, improved occupant egress, and fuel containment have high priority. This subject has been treated in the SAFER committee recommendations (ref. 69). Structural crash response is concerned with tank rupture mechanisms and with cabin interior equipment. Fuselage structural integrity also plays an important role in the postfire hazard by preventing entry of fuel, fire and smoke through breaks in the fuselage and in protecting established egress routes by maintaining the floor structure and operable doors and hatches.

The role of main landing gear in maintaining ground clearance for the wing and fuselage has been seen in section 4. A gear with increased resistance to separation in rough terrain may reduce the likelihood of wing tank breaks and tank lower surface tears, engine pod separation, and could also eliminate some friction fires.

In addition, fuselage structural integrity provides the occupant with a protective shell and with energy absorbing load paths. Methods of increasing break resistance of the fuselage are needed. Similarly, optimization of fuselage energy absorption is needed. Improvement of structural integrity will tend to reduce trauma injury.

Occupant injury reduction is concerned with floor/seat/occupant/restraint systems. The system nonlinear dynamic response needs to be understood. Current commercial practice defines the problem in terms of static enveloping values based on accident experience. For new lightweight seats, the effect of departures from proven designs on occupant hazards or injury potential should be understood. Of particular concern is dynamic response of the occupants in new seats as compared to conventional seats as both seat and occupant interact with floor acceleration pulses. This response involves the complete seat system from floor structure and seat attachments to impacting surrounding objects. A similar problem exists for the conventional seat to a lesser extent. Research into the effects of the pulse on both the seat and occupant is needed.

Methods of accident-envelope analyses are needed for assessing crash performance of aircraft and structural components. Such methods provide a means for parametric studies and extrapolation from crash test and accident data to other scenario conditions. Proven simulation techniques are necessary for engineering purposes.

Crash performance assessment of the aircraft and structural components needs improvement. Since cost of full-scale aircraft tests precludes many tests, it is important to extract as much engineering data as possible from accidents. For some accidents, in which the aircraft has not been completely destroyed, additional support to the NTSB by impact dynamics research personnel from NASA and the FAA may produce more data. This data is needed to study accident behavior

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Current aircraft
      Fire hazards
      Structural integrity
      Trauma injury
      Crash envelope analysis
      Crash performance assessment

Advanced aircraft
      Material performance
      Component performance
      Aircraft occupant protection concepts

Full scale crash tests
      B720 test
      Future full scale crash tests
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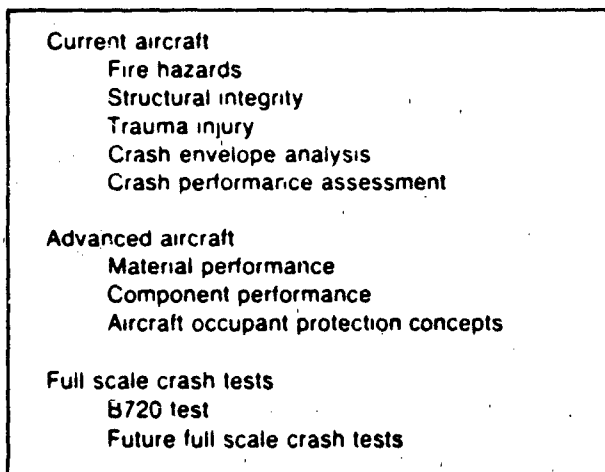
Figure 6.1-Structural Crashworthiness Problem Areas

with analytical methods and for simulation testing of structural components. In addition, such data will be useful in refinement of the accident scenarios.

Advanced aircraft problems are concerned with the introduction of advanced materials, graphite/epoxies in particular. Problem areas exist in material crash performance, advanced component performance, and with aircraft occupant protection concepts. Problems with material performance includes high energy impact resistance and burn characteristics. Design latitude afforded by these materials in ply orientation and introduction of modifying materials may permit desirable impact characteristics to be achieved. With regard to burn characteristics, these advanced materials may provide protection to the occupant by not melting in the presence of a heat pulse while retaining a char barrier and by reduced friction sparking.

Crash performance of structural components made from advanced materials must be compared to that of current structural components. Differences in performance must be assessed for their effect on accident performance of the complete aircraft. Impact response mechanisms of advanced components must be understood in order that accident performance might be optimized.

New occupant protection concepts for advanced aircraft may be required. Current metal aircraft have inherent properties contributing to crashworthiness provisions in addition to other design conditions that may not be present in advanced aircraft. Consequently, it may be necessary to introduce new approaches to occupant protection.

Since accident performance of full-scale aircraft has such an important role in crashworthiness, problems of testing full-scale aircraft must be addressed. In addition to technical problems of test methods, data acquisition, and reduction, the severity levels of the tests must be within the envelope of survivable accidents for maximum application of the results. This requires further refinement of the accident scenarios and implies some knowledge of human injury tolerance. These problems should be resolved prior to the planned test of the 720 aircraft.

RECOMMENDED RESEARCH AND DEVELOPMENT

A research and development program is presented. One objective is to understand the crash response of current designs and to develop structural impact technology that might improve current commercial jet transport aircraft and serve as a basis for the assessment of advanced aircraft structure. A second objective is to understand the crash performance of advanced structural components. A third objective is to obtain crash environmental data from full-scale complete aircraft tests for validation of technology and for assessment of crash scenarios. Recommendations are given for current metal aircraft, advanced aircraft, and for full-scale complete aircraft tests.

CURRENT METAL AIRCRAFT

Research on reduction of the postcrash fire hazard is recommended. SAFER Committee recommendations on fuel additives, fire resistance, and fuel containment technology are supported.

With respect to the structural role in fuel containment, research into the various mechanisms of tank rupture is recommended. Experimental and analytical methods of simulating tank rupture in crash conditions should be developed. Research should include full-scale aircraft and component testing of structural improvements and of devices or techniques to reduce the fuel flow rate from fractured tanks.

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To improve occupant egress, the effects of representative crash accelerations and displacements on containment of cabin interior equipment and contents should be determined. Galleys, overhead compartments, ceiling panels, lighting, and other interior appointments should be studied to reduce blockage of egress routes. For water entry, new designs and techniques for storage and deployment of life rafts and floatation equipment that will facilitate egress and eliminate blockage of exits should be developed.

Research to improve structural integrity of the fuselage is recommended. Studies into the mechanisms of fuselage breaks, maintenance of protective shell, optimization of energy absorption, distortions at doors and hatches and floors for the crash scenarios should be done. To accomodate water entry, studies of design improvements that will eliminate tearing and rupturing of the fuselage lower surface by hydraulic action of the water (some inward crushing would be tolerable) thus improving the floatation capability should be done.

Main landing gear accident performance in rough terrain should be studied. Crash loads and displacements for existing gear concepts for representative hazards should be determined. The interaction of the gear and the attaching structure should be understood. Advanced concepts for improved crash performance should be developed.

Research for trauma injury reduction is recommended. Studies to ascertain the effects of fuselage structural arrangement on the acceleration impulse and floor displacement experienced at the points of seat attachment should be conducted. Effects of the shape, magnitude, and duration of the seat acceleration impulse on seat/occupant/restraint system response should be obtained for current seats and for new lightweight seats. Also seat capability in terms of both static and dynamic loading should be established. Effects of occupant parameters such as mass, size, distribution, occupant accelerations, restraint effectiveness and seat deformation should be obtained. Effort should be made to relate engineering measurements to occupant injury and injury indices.

Crash envelope analyses need to be developed for assessment of crashworthiness. Existing computer programs such as KRASH and DYCAST may serve as a starting point. Limits of validity of such analyses need to be established. Methods of accident simulation and the data base to support this approach should be developed. The technology of these methods should be extended.

Research for crash performance assessment should be done to refine the accident scenarios. Efforts to obtain data from selected accidents to better define the initial conditions and the sequence of events are needed. Engineering data for accident simulation should be obtained.

ADVANCED AIRCRAFT

Research is recommended in high energy impact for advanced materials such as graphite/epoxy. Effects of design parameters on impact resistance should be determined. Ways to increase impact resistance and burn characteristics should be sought.

With respect to advanced components, a program to determine crash performance should be conducted. Analytical and experimental crash simulations should be made. Advanced component performance should be compared to current components and differences identified. Methods of modifying the performance should be explored.

It is anticipated that impact resistance of advanced materials and energy absorption characteristics of components made of these materials may be sufficiently different from current metal aircraft that new concepts of occupant protection might be needed. Of particular concern are

wing tanks, fuselage integrity including energy absorption, and the floor/seat/ occupant/restraint system. New approaches to occupant protection should be investigated.

FULL-SCALE CRASH TESTS

The planned 720 crash test should be instrumented to obtain data on structural components and seat/occupant/restraint systems. Crash response modes and loads on both the structural components and the seat/occupant/restraint system should be obtained. Full-scale tests should be used to refine the scenario.

Depending on the success of the 720 test, additional full scale crash tests should be considered. Future tests would serve to evaluate other scenarios and to more completely define the crash environment and crash response mechanisms. They would also be useful for validation of analytical methods. As advanced materials are incorporated into future aircraft, full-scale tests for occupant protection concept validation should be considered. An objective of this program is to minimize the need for full-scale crash tests.

RECOMMENDED PROGRAM

The program recommended for inclusion in the planning for the NASA/FAA Crashworthiness Research program for General Aviation and Commercial Jet Transport Aircraft is given. While the complete development of the crashworthiness technology is a worthy goal only major segments are suggested.

Major segments of the program are identified. A strong emphasis is placed on the performance of advanced composites. The segments include fuel containment, fuselage integrity/energy absorption, floor/seat/occupant response, complete aircraft response, accident investigation, component performance, and support technology. The elements of these segments have been discussed in the body of the study and in section 5 in particular.

A tentative schedule through 1990 for the recommended segments in the NASA/FAA research and development program pertaining to commercial jet transport aircraft is shown in figure 6.2. The schedule is based on task priority, current state of the technology, estimates of available facilities, and timeliness to aircraft applications.

Boeing Commercial Airplane Company
   P. O. Box 3707
     Seattle, Washington 98124
       August 10, 1981

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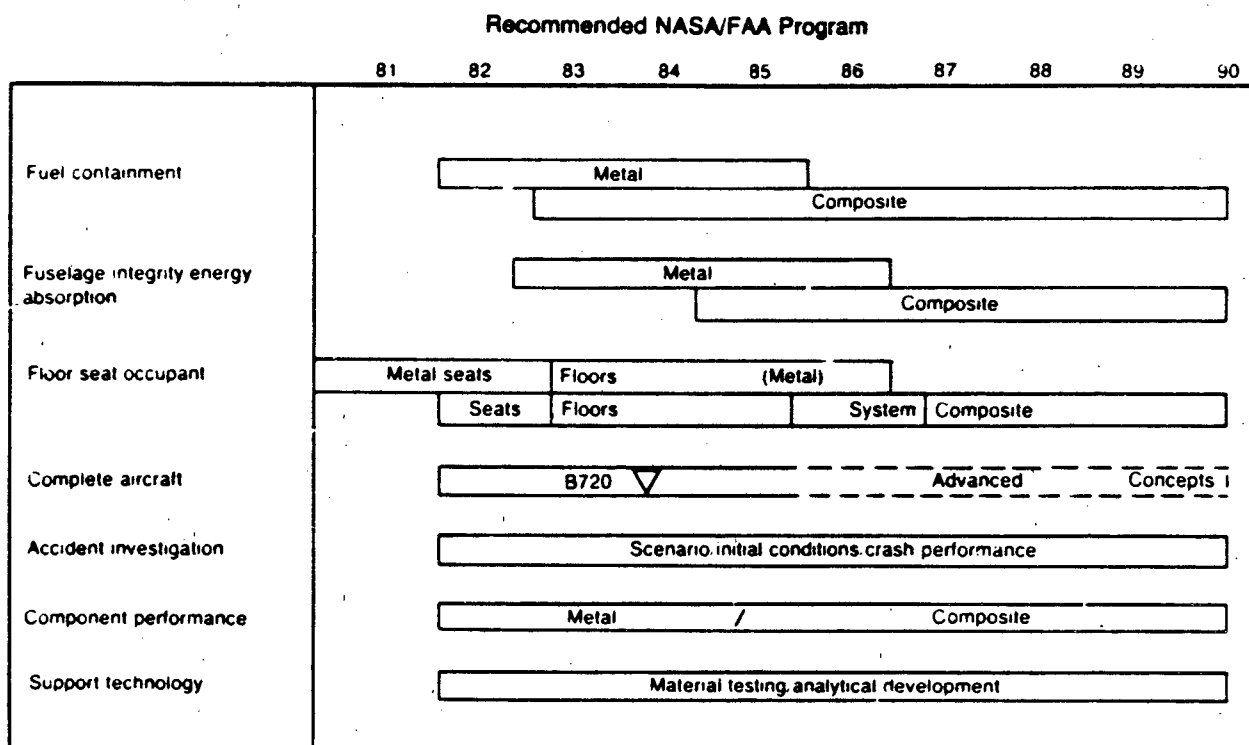
Figure 6.2–Commercial Transport Structural Crashworthiness

APPENDIX A

Accident Definition

(As Defined by the National Transportation Safety Board)

"Aircraft accident" means an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, in which any person suffers death or serious injury as a result of being in or upon the aircraft or by direct contact with the aircraft or anything attached thereto, or the aircraft receives substantial damage.

"Operator" means any person who causes or authorizes the operation of an aircraft, such as the owner, lessee, or bailee of an aircraft.

"Fatal injury" means any injury which results in death within 7 days.

"Serious injury" means any injury which (1) requires hospitalization for more than 48 hours, commencing within 7 days from the date the injury was received; (2) results in a fracture of any bone (except simple fractures of fingers, toes, or nose): (3) involves lacerations which cause severe hemorrhages, nerve, muscle or tendon damage: (4) involves injury to any internal organ; or (5) involves second or third degree burns, or any burns affecting more than 5 percent of the body surface.

"Hull loss" means damage due to an accident which was too extensive to repair or, for economic reasons, the aircraft was not repaired and returned to service.

"Substantial damage"

(1) Except as provided in subparagraph (2) of this paragraph, substantial damage means damage or structural failure which adversely affects the structural strength, performance, or flight characteristics of the aircraft, and which would normally require major repair or replacement of the affected component.

(2) Engine failure damage limited to an engine; bent fairings or cowling; dented skin; small punctured holes in the skin or fabric. Damage to landing gear, wheels, tires, flaps, engines accessories, brakes, or wing tips are not considered "substantial damage" for the purpose of this part.

A "survivable" accident is one in which the fuselage remains relatively intact, the crash forces do not exceed the limits of human tolerance, there are adequate occupant restraints, and there are sufficient escape provisions.

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APPENDIX B

The following 1980 accidents would be good candidates for additional study:

1. 707   2/27/80   China, Manila, hull loss, 3 of 135 were fatalities, severe fire, hard touchdown, wing failed.

2. 707   5/11/80   Sobelair, Doucela, Cameroon, hull loss, no fatalities, no fire, veer off.

3. L-1011   8/19/80   Saudi, Riyadh, hull loss, 301 fatalities, cabin fire in flight, landed but no evacuation.

4. 727   9/3/80   Pan Am, San Jose, Costa Rica, hull loss, no fatalities, touchdown short, no fire.

5. 737   10/6/80   Air Florida, Port au Prince, substantial damage, no fatalities, veered off runway, separated gear, fuel leak through crack in fitting.

6. 747   11/19/80   Korean, Seoul, Korea, hull loss, 14 of 226 were fatalities, severe fire (nonfuel) touchdown short, gear separated.

7. 727   11/21/80   Air Micronesia, Yap Island, hull loss, veered off runway, no fatalities, severe fire.

8. 707   12/20/80   Aerotal, Bogota, hull loss, no fatalities, touchdown short, severe fire.

APPENDIX C

This form appearing on the following pages was used for the data search of the accidents. It is presented here as a convenience to the reader.

ACCIDENT FILE NO. _____

ACCIDENT IDENTIFICATION

DATE _____   TOTAL ONBOARD _____

A/C MODEL _____   CREW (+NON-REV.) _____

AIR CARRIER _____   PASSENGERS _____

LOCATION _____   TOTAL FATALITIES _____

TIME (LOCAL) _____   TOTAL SERIOUS INJURIES _____

FLIGHT PHASE _____   IMPACT SURVIVABLE YES _____ NO _____

DAMAGE, (HULL, MAJOR) _____

TYPE OF ACCIDENT _____   TERMINATE IN WATER _____

_____   IN-FLIGHT FIRE

_____   GROUND IMPACT - NO FIRE

_____   GROUND IMPACT - MINOR FIRE

_____   GROUND IMPACT - MOD. FIRE

_____   GROUND IMPACT - SEVERE FIRE

DESCRIPTION OF ACCIDENT _____

_____

_____

_____

STRUCTURE RELATED TYPE

NO STRUCTURE DESCRIPTION _____   COCKPIT DAMAGE _____

FUSELAGE BREAK _____   WING TIP _____

BELTS/SEAT SEP _____   GEAR SEP _____

TANK RUPT _____   ENGINE/PYLON SEP _____

FLOORS _____   DOORS _____

DEBRIS _____   FUEL LINES _____

WEATHER   TEMP. _____   WIND _____

DESCRIPTION AT IMPACT LOCATION _____

_____

TERRAIN AT IMPACT LOCATION _____

_____

A/C ATTITUDE AT IMPACT _____

_____

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PILOT ACTIONS

    FLIGHT DATA RECORDER ANALYSIS _____FLAPS _____

    AVOIDANCE ACTIONS

        ROTATION _____ SPOILERS _____ FLAPS _____

        BRAKES _____ REVERSE THRUST _____ POWER _____

        STEERING _____ OTHER CONTROL APPLICATIONS _____

A/C CONFIGURATION AT IMPACT

GEAR   L MLG _____ R MLG _____ NOSE GR _____

EST. FUEL QT. GAL. NO. 1 _____ NO. 2 _____ CW _____ NO. 3 _____ NO. 4 _____

AT IMPACT - A/C SPEED _____ RATE OF DESCENT _____

IMPACT "G" LOADS - FWD _____ DOWN _____ SIDE _____

WING DAMAG/FUEL SPILL

HOW AND WHERE SPILLED _____

WING BOX RUPT BY GEAR SEP _____ OR ENGINE STRUT SEP _____

QUANTITY SPILLED MAJOR _____ MOD _____ MINOR _____

SEPARATION AT W.S. - LEFT _____ RIGHT _____

X-RUPT X-EXPLO. TANK RUPTURE NO. 1 ____ NO. 2 ____ CW ____ NO. 3 ____ NO. 4 ____

ENGINE SEPARATION NO. 1 _____ NO. 2 _____ NO. 3 _____ NO. 4 _____

ENG. STRUT. SEP. NO. 1 _____ NO. 2 _____ NO. 3 _____ NO. 4 _____

LDG. GEAR SEP. OR COLLAPSE L MLG _____ B MLG _____ R MLG _____ N.G. _____

WING FUEL FIRE - WHICH TANK(S) _____

            - WHICH ENGINES OR STRUTS _____

    SEVERITY EXTREME _____ MODERATE _____ MINOR _____

SOURCE OF IGNITION _____

HOW LONG (TIME IN SECONDS) AFTER A/C MOVEMENT STOPPED UNTIL FIRE BECAME SEVERE

FUSELAGE DAMAGE

CABIN FLOOR DAMAGE _____

FUSELAGE BREAK LOCATIONS (BODY STA. S) _____

    TOTAL SEPARATION _____ PARTIAL SEP. _____

COCKPIT DAMAGE EXTREME _____ MODERATE _____ MINOR _____

PASS. SEAT SEP. MOST _____ SOME _____ FEW _____ NONE _____

GALLEY SEPARATION (WHICH) _____

OVERHEAD STORAGE COLLAPSE _____

BODY INTERIOR PANEL COLLAPSE _____

WHAT DEBRIS HINDERED PASS EVAC. _____

_____

FUSELAGE DOOR/HATCHES   WERE - JAMMED _____

                                     - BLOCKED _____

EXTERNAL FUEL FIRE ENTERED PASS. AREA (HOW OR WHERE) _____

_____

LWR (BOTTOM) FUSELAGE TORN/RUPT. - EXTREME _____ MOD. _____ MINOR _____

FUSELAGE FIRE (NON-FUEL) - INITIAL LOC. _____

                - IGNITION SOURCE _____

     SIZE/EXTENT OF BURN AREA _____

_____

VENTILATION PROBLEM - SMOKE/FUMES

     COCKPIT   - SEVERE _____ MOD. _____ MINOR _____ NONE _____

     UNKNOWN _____

     PASS CABIN - SEVERE _____ MOD. _____ MINOR _____ NONE _____ UNKNOWN _____

AFT FUSELAGE - TAIL MOUNTED ENGINE A/C

ENGINE BURST DEBRIS DAMAGED FUSELAGE (LOCATIONS) _____

_____

               - FIRE DEVELOPED IN FUSELAGE _____

_____

ENGINE/STRUT FIRE BURNED INTO FUSELAGE _____

_____

FIRE/SMOKE ENTERED PASS. COMPT. SEVERE _____ MOD. _____ MINOR _____

FIRE (OTHER THAN ENGINE RELATED) _____

_____

CREW & PASSENGER EVACUATION

TIME TO EVAC SURVIVORS (SECONDS) _____

NUMBER OF PASS. THAT EVACUATED THRU   ENTRANCE DOORS _____

                                EMERG. HATCHES _____

                                BODY BREAKS _____

                                UNKNOWN _____

SLIDES/CHUTES - NOT USED _____   USED SUCCESSFULLY _____

    SOME MALFUNCTED (NO.) _____   EFFECTED EVAC. _____

    SOME RIPPED OR BURNED (NO.) _____   EFFECTED EVAC. _____

SURVIVORS THROWN OUT THRU BODY BREAKS _____

TOTAL NO. FATALITIES AT SCENE   _____   PASS/CREW

    NUMBER

    NUMBER FOUND IN SEATS   _____   PERCENT

    IN AISLE (ON FLOOR)   _____   MOST

    OUTSIDE A/C   _____   FEW

    UNKNOWN   _____   SOME, ETC.

CAUSE OF DEATH - TRAUMA -   INSIDE A/C _____   PASS/CREW NUMBER

                          OUTSIDE A/C_____   PERCENT

        -FIRE/SMOKE -   INSIDE A/C _____   MOST

                          OUTSIDE A/C_____   FEW

        -UNKNOWN   _____   SOME, ETC.

PANIC MAY HAVE _____ DID OCCUR _____ OR UNKNOWN _____

FATALITIES MAY HAVE _____ DID _____ RESULT FROM THIS

EMERG. LIGHTING USED _____ NOT USED _____ UNKNOWN _____

AIRCRAFT TERMINATED IN WATER

TIME (MIN.) A/C REMAINED AFLOAT _____ ALL OR PART _____

A/C RESTS ON BOTTOM (PARTIALLY OUT OF WATER) _____

SLIDES/RAFTS   USED _____   NOT USED _____   UNKNOWN _____

LIFE VESTS   AVAILABLE _____   USED _____   NOT USED _____   UNKNOWN _____

FUSELAGE REMAINED INTACT _____   BROKEN/SEP _____   RUPTURED _____   UNKNOWN _____

FATALITIES DUE TO TRAUMA   _____   NUMBER

    DROWNING   (INSIDE A/C)   _____   PERCENT

                (OUTSIDE A/C)   _____   MOST

                UNKNOWN   _____   SOME

                                              FEW, ETC.

JUDGEMENT ITEMS   (SEVERITY INCLUDES BOTH A/C DAMAGE & FATALITIES)

GEAR SEPARATION/COLLAPSE CONTRIBUTED TO SEVERITY OF THIS ACCIDENT

                        DID   _____

                        MAY HAVE   _____

                        DID NOT   _____

ENGINE/PYLON SEPARATION CONTRIBUTED TO THE SEVERITY OF THIS ACCIDENT

                        DID   _____

                        MAY HAVE   _____

                        DID NOT   _____

FUEL TANK REPTURE CONTRIBUTED TO THE SEVERITY OF THIS ACCIDENT

                        DID   _____

                        MAY HAVE   _____

                        DID NOT   _____

FLOORS/DOORS/DEBRIS CONTRIBUTED _____

                        DID   _____

                        MAY HAVE   _____

                        DID NOT   _____

BELTS/SEATS _____

                        DID   _____

                        MAY HAVE   _____

                        DID NOT   _____

FUSELAGE BREAK/SEPARATION CONTRIBUTED TO SEVERITY OF THIS ACCIDENT

                        DID   _____

                        MAY HAVE   _____

                        DID NOT   _____

APPENDIX D

Review/Appraisal of the U.S. Army's, Aircraft Crash Survival Design Guide USARTL-TR-79-22A,B,C,D,E for Other Applications

D.L. Parks

D.W. Twigg

ABSTRACT

The newest update to the U.S. Army's Aircraft Crash Survival Design Guide for Army aircraft was reviewed for ideas that might apply in other systems and therefore bear further research. Philosophically, many features were compatible with the philosophy and practices for commercial systems. However, the Guide does not make allowances for widely varying differences in crash characteristics and inherent energy absorption features from one system to another, e.g., from small rigid body aircraft with minimal subfloor volume for energy absorption to large flexible body aircraft with large subfloor volume for energy absorption. Additionally, the orientation is for survival under any circumstances that Army operations might encounter—a far more hazardous set of circumstances than will occur for commercial vehicles. Accordingly, this appraisal does not get into all criteria in the Guide but instead provides a review of those features that may bear further consideration in research and development studies.

1.0 INTRODUCTION

The purpose of the present study is to review and critique the new U.S. Army's Crash Survival Design Guide (ref. D-1) for research ideas that might ultimately benefit commercial aircraft safety and thus bear further research attention to resolve potential value in commercial aircraft applications. It is also intended to distinguish those elements which may and which may not readily transfer from light and small rigid body aircraft to large flexible body transports.

The authors of the new Guide accepted and are to be commended for responding to a major challenge. They have attempted to refine earlier editions of the Guide and to indicate more room for trade-offs than earlier issues implied. For example, the third edition of the Army Crash Survival Design Guide more carefully constrains the guideline recommendations to the small rigid body airplanes used by the U.S. Army than earlier editions, i.e., the light fixed wing aircraft and helicopters. Additionally, the authors indicate many of the trade-offs and realistic constraints that must be considered relative to the guidelines, introducing the possibility of waivers by the Army, based on trade-offs of objectives versus realistic design constraints. The indicated trade-offs illustrate potential problems in generalizing within vehicles, and by extension problems in attempts to generalize guidelines developed for the Army to large flexible body commercial airplanes.

Since the 1967 and 1971 versions of the Guide, many areas of progress in development, in test and evaluation, and in operational experience have added to the fund of knowledge. However, guidelines or criteria spelled out in the earlier Guide were in fact sometimes unduly restrictive, sometimes difficult-to-impossible to achieve, and conservative even for the Army objectives. In this latest version of the Guide, these constraints are more apparent, more need for tradeoffs from the "criterion" conditions are recognized, and distinctions between military and commercial environments are more obvious. However, and perhaps partially due to the greater autonomy the Army has as both purchaser and user, the new Guide does not yet really address minimum requirements that must be met; the orientation remains one of setting goals as trade-off positions.

The new Guide is in five volumes. In this appendix, information is abstracted, collated and synthesized across the five volumes to integrate the information into one single abstract summary. This summary is a synthesis and critique of the U.S. Army's Aircraft Crash Survival Design Guide in that it is in the main constrained to research possibilities for other systems. Accordingly, it includes information that may be relevant for commercial aircraft research efforts, and includes questions regarding the Army Guide position. Since there was significant overlap and some considerable redundancy between volumes, a major element in the present effort was to abstract and correlate related information from all volumes. Information herein follows the same general format. Volume titles and contents are as follows:

Volume I — Design Criteria and Checklists
   Pertinent criteria extracted from Volumes II through V. Provides for updating earlier related military standards (ref. D-1).

Volume II — Aircraft Crash Environment and Human Tolerance
   Crash environment, human tolerance to impact, military anthropometric data, occupant environment, test dummies, accident information retrieval.

Volume III — Aircraft Structural Crashworthiness
   Crash load estimation, structural response, fuselage and landing gear requirements, rotor requirements, ancillary equipment, cargo restraints, structural modeling.

Volume IV — Aircraft Seats, Restraints, Litters, and Padding
Operational and crash environment, energy absorption, seat design, litter requirements, restraint system design, occupant/restraint system/seat modeling, delethalization of cockpit and cabin interiors.

Volume V — Aircraft Postcrash Survival
Postcrash fire, ditching, emergency escape, crash locator beccons, retrieval of accident information.

General types of subjects covered include:

1. Crashworthiness of Aircraft Structure—The ability of the aircraft structure to maintain living space for occupants throughout a crash.

2. Tiedown Strength—The strength of the linkage preventing occupant, cargo, or equipment from becoming missiles during a crash sequence.

3. Occupant Acceleration Environment—The intensity and duration of accelerations experienced by occupants (with tiedown assumed intact) during a crash.

4. Occupant Environment Hazards—Barriers, projections, and loose equipment in the immediate vicinity of the occupant that may cause contact injuries.

5. Postcrash Hazards—The threat to occupant survival posed by fire, drowning, exposure, etc., following the impact sequence.

To date three editions of the Guide have been released, the first in 1967, an update in 1971, and a total revision in 1979.

BACKGROUND DISCUSSION

As summarized in the new Aircraft Crash Survival Design Guide, the U.S. Army Transportation Research Command (now the Applied Technology Laboratory, Research and Technology Laboratories of the U.S. Army Aviation Research and Development Command (AVRADCOM) initiated a long-range program in the early 1960s, with the objective to study all aspects of aircraft safety and survivability. From this program, it was intended to determine improvements in crash survival that could be made if consideration were given in the initial aircraft design to general survivability factors; figure D-1.1 expands on aspects of "Crashworthiness" as defined by the newest version of the Guide.

In order to determine which criteria and guidelines might be appropriate for commercial aircraft for present purposes, it was necessary to determine the purpose of individual guidelines and criteria. The reason is that criteria and guidelines are not usually directly transferable. For example, design criteria levels in the Guide are not based on theory; rather they are obtained by estimating the crash loads which occurred in past crashes of light, rigid body Army aircraft. In turn, a number of related assumptions were involved. Large, flexible body commercial aircraft with a large cargo hold in the lower fuselage are clearly different in design features that will affect crash loads and probable dynamic responses in direct contrast to those expected for the smaller and lighter rigid body Army aircraft. Accordingly, the conditions upon which criteria are based must differ.
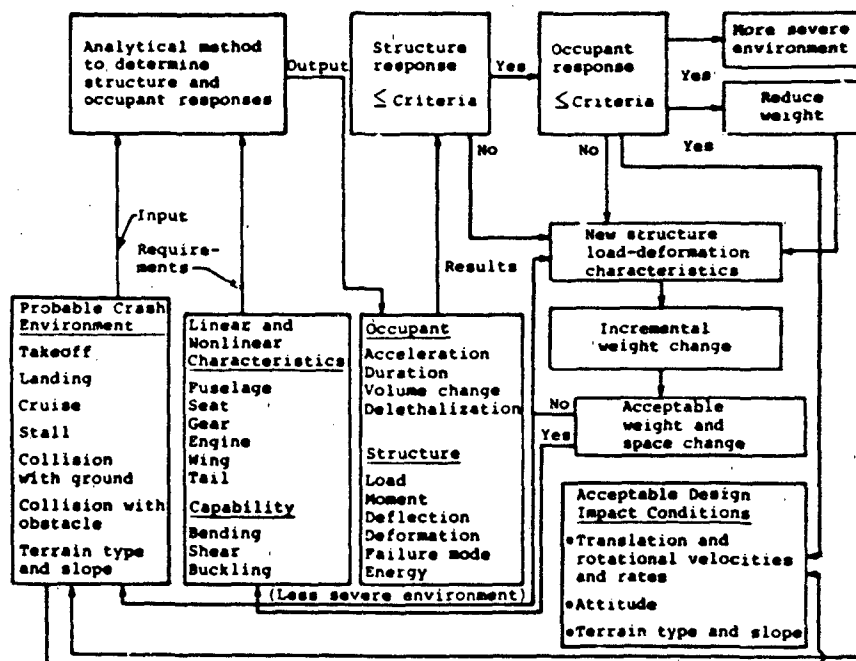
Procedure for evaluation of structural designs with respect to crashworthiness.

CRASHWORTHINESS CRITERIA FOR THE PRELIMINARY DESIGN PROCESS

Crash scenarios	Primary structure	Energy absorption	Postcrash requirements
• MIL-STD-1290(AV) defines predominant impact conditions	• Support of large mass items	• Landing gear	• Emergency egress
	• Support of systems	• Controlled structural collapse	• Occupant release from seats
• Single axis and combination of:		• Crashworthy energy-absorbing seats	• Door/exit opening
• Vertical impact	• Occupant support and protection		• Accessibility of exits
• Longitudinal impact	• Cargo containment and tiedown	• Shedding of large mass items	• Minimization of postcrash fire hazards
• Lateral impact	• Support of landing gear loads	• Engines • Transmissions • Rotor heads	
• Postimpact • Rollover • Pitchover • Nose plowing	• Space consistent with occupant strike envelope	• External stores • Tail boom (Shed items must not impact occupied areas)	• Fuel containment • Oil and hydraulic fluid containment
	• Emergency exit structure	• Impacted surface (soft ground etc.)	• Fuel modification • Ignition source control • Reduce material flammability, smoke and toxicity

Note: Data from Army CSDG.

Figure D-1.1 – Crashworthiness Procedures for Structural Designs and Criteria for Preliminary Design Process

The new Aircraft Army Crash Survival Design Guide gives three distinctly different descriptions of the purpose of crashworthy designs, but all with the same criterion levels: (1) to eliminate unnecessary injuries and fatalities in relatively mild impacts (COMMENT: "unnecessary" is not defined), (2) to contain occupant deceleration levels within human tolerance in severe crash environments, or (3) (by numerous implications) to survive any crash "combat ready". All three criteria in the Guide refer to the same deceleration levels. In contrast, Federal Air Regulation Part 25 (FAR 25) states that design for commercial aircraft is "to give each occupant every reasonable chance of escaping serious injury in a minor crash landing" when using restraints and other safety provisions, with landing gear up, and with lower deceleration loads and uses a correspondingly lower criterion level.

On the surface, the first two goals of crashworthy design stated in the Guide (to eliminate unnecessary injuries and fatalities in a minor crash and to assure survival in a severe crash—still a somewhat speculative outcome) may seem consistant. In actuality, the two goals are frequently in opposition. A design feature designed to operate at low crash loads to prevent injury is often inefficient at high crash loads, and presence of the feature may in fact degrrde the overall performance at the high loads. This is an extension of the comfort versus safety problem—a system designed to be comfortable at low crash loads may very likely be less "safe" at high crash loads. An example is the 5 mph barrier crash requirement in the automotive industry. Bumper systems designed to provide 100% protection (to the car) at 5 mph may provide less protection at higher speeds than might otherwise be the case. Unfortunately, the Guide appears to treat these criteria as though they were interchangeable.

"Survivable" commercial aircraft accidents are generally near airports where external assistance for evacuation and quick medical attention are available. Thus, even the injured have a reasonable chance for survival. This is in stark contrast with military crashes, which may occur in a combat zone without prospect of external aid so that the need for self sufficiency is more pronounced. Goals to totally avoid injury are vastly different from goals to reduce injury potential or otherwise improve safety in even the feasibility of implementing practical improvements.

As its own regulator and consumer, the Army can set and adjust goals and thus need not distinguish between crashworthiness goals, guidelines, and criteria. As pointed out in Volume II, the Army may itself opt to retain, adjust, or waive any of same when compliance is demonstrated to involve an unacceptable compromise in system objectives, performance, or costs. These distinctions are, accordingly, not rigidly observed in the new Guide. Neither the lack of distinction in goals, guidelines and criteria nor waivers are practical in the civilian environment. Rules are laws that must be met without exception and cannot be traded off when a given requirement is demonstrated to be impractical, or shown to effect a serious compromise some other aspect of system operation.

It should be emphasized that the Army's design guide was written expressly for the Army's light aircraft (helicopter and single engine propeller), which must include, by definition, operations involving a variety of "normal", training, remote austere, and combat situations. The aircraft considered for the updated version of the guide were constrained to a vehicle mission gross weight of 12,500 pounds or less.

2.0 DEFINITIONS OF TERMS

The Guide defines specialized terms related to crashworthiness at the beginning of each volume. Several of these definitions are paraphrased herein for the convenience of the reader.

GENERAL TERMS

Abrupt Decelerations — Describes the short duration shock accelerations primarily associated with crash impacts, ejection seat shocks, capsule impacts, etc. One second is generally accepted as the dividing point between abrupt and prolonged accelerations. Within the extremely short duration range of abrupt accelerations (0.2 sec and below), the effects on the human body are limited to mechanical overloading (skeletal and soft tissue stresses), there being insufficient time for functional disturbances due to fluid shifts.

COMMENT: Within the Guide, high loads used to define criteria are less than one second duration and most typically less than .050 sec. The authors state that this region is where effects on the human body are limited to mechanical overload of structure and tissue since time is too short for fluid shifts. In large commercial aircraft, pulses are generally accepted as ranging up to 0.2 to 0.25 seconds.

Human Tolerance — A selected array of parameters that describe a condition of human body decelerative loading, i.e , a crash pulse for which it is believed there is a reasonable probability of survival without major injury (this is also termed "whole-body tolerance"). "As used in this volume (III), designing for the limits of human tolerance refers to providing design features that will maintain these conditions at or below their tolerable levels to enable the occupant to survive the given crash environment."

Human tolerance to the crash environment is a function of many variables, including unique characteristics of each person as well as the impinging loads. Loads are transmitted from the seat, the restraint system and the surrounding environment. Tolerability depends on load direction, body orientation, and the critical nature of the load relative to a body member. For example, conditions wherein the belt rides up off the iliac crests of the pelvis may contribute excessive abdominal loads, or skull fracture may result from head contact, or the type of loads applied to the spine may create injury.

COMMENT: Definition implies that it is possible and practical to design to human tolerance limits and assure survival without exception; in actuality, other text clearly indicates this to be considered a goal which is not necessarily achievable. Resulting implications are misleading to the newcomer to the field.

The Term "G" — Refers to the ratio of acceleration encountered to that from gravitational attraction on a given body at sea level, (i.e., relative to 32.2 ft/sec^2). In use herein, "G" increments are referenced in multiples of same, so 5 G is 5 times the normal forces on the body.

Survivable Accident — An accident in which the forces to the occupant(s) are within tolerance limits and the surrounding structure remains substantially intact to provide a livable volume throughout the crash sequence.

COMMENT: Definition of survivability varies between volumes of the Guide. One is to "eliminate unnecessary injuries and fatalities in relatively mild impacts" (Volume I). Another is to "minimize occupant accelerations to survivable levels in a severe crash environment" (Volume II).

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Survival Envelope — The range of impact conditions wherein the occupiable area of the aircraft remains substantially intact, (i.e., wherein forces transmitted to occupants do not exceed the limits of human tolerance when state-of-the-art restraint systems are used). As a precaution, accident investigation will not necessarily show that survivable conditions may not have existed in an accident that may appear from postcrash inspection to have been survivable; elastic recovery from crash induced deformation can mask actual crash conditions.

Submarining — The rotation of the hips under and through the lap-belt as the belt slips up and off the iliac crests of the pelvis caused by forward inertial loads on the legs. "Lap-belt slippage" can be a direct result of the upward loading of the shoulder harness straps at the center of the lap-belt. (figure D-2.1, from ref. D-2).

Dynamic Overshoot — The amplification of decelerative force on cargo or personnel above the impact deceleration force resulting from dynamic response of the system. For example, a loose system can dramatically increase peak loads.

SEATING GEOMETRY

See figure D-2.2, from MIL-STD-1333, MIL-STD-850, and U.S. Army's Aircraft Crash Survival Design Guide (ref. D-3, D-4, and D-1).

Design Eye Position — A reference datum point based on the eye location that permits the specified vision envelope required by MIL-STD-850, allows for slouch, and is the datum point from which the aircraft station geometry is constructed. The design eye position is a fixed point in the crew station, and remains constant for pilots of all statures via appropriate seat adjustment.

Horizontal Vision Line — A reference line passing through the design eye position parallel to the true horizontal and normal cruise position.

Back Tangent Line — A straight line in the midplane of the seat passing tangent to the curvatures of a seat occupant's back when leaning back and naturally compressing the back cushion. The seat back tangent line is positioned 13 in. behind the design eye position as measured along a perpendicular to the seat back tangent line.

Buttock Reference Line — A line in the midplane of the seat parallel to the horizontal vision line and tangent to the lowermost natural protrusion of a selected size of occupant sitting on the seat cushion.

Seat Reference Point (SRP) — The intersection of the back tangent line and the buttock reference line. The seat geometry and location are based on the SRP.

Buttock Reference Point — A point 5.75 in. forward of the seat reference point on the buttock reference line. This point defines the approximate bottom of an ischial tuberosity, thus representing the lowest point on the pelvic structure and the point that will support the most load during downward vertical loading.

Heel Rest Line — The reference line parallel to the horizontal vision line passing under the tangent to the lowest point on the heel in the normal operational position, not necessarily coincidental with the floor line.

SELECTED EXAMPLES
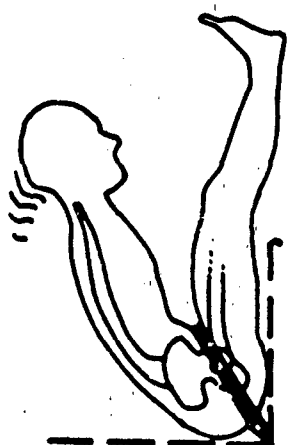
JACKKNIFING
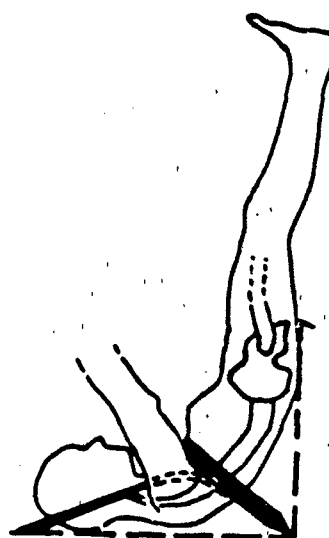
TORSO THROWN FORWARD UNDER THE BELT
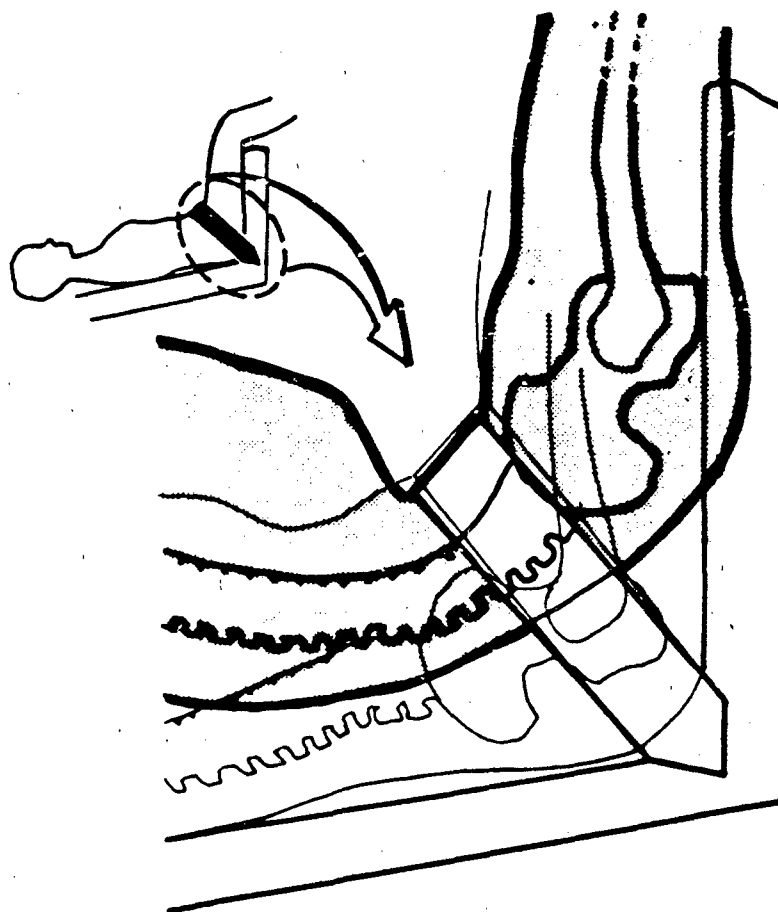
SUBMARINING

Figure D-2.1 – Dynamic Responses to Forward Accelerations
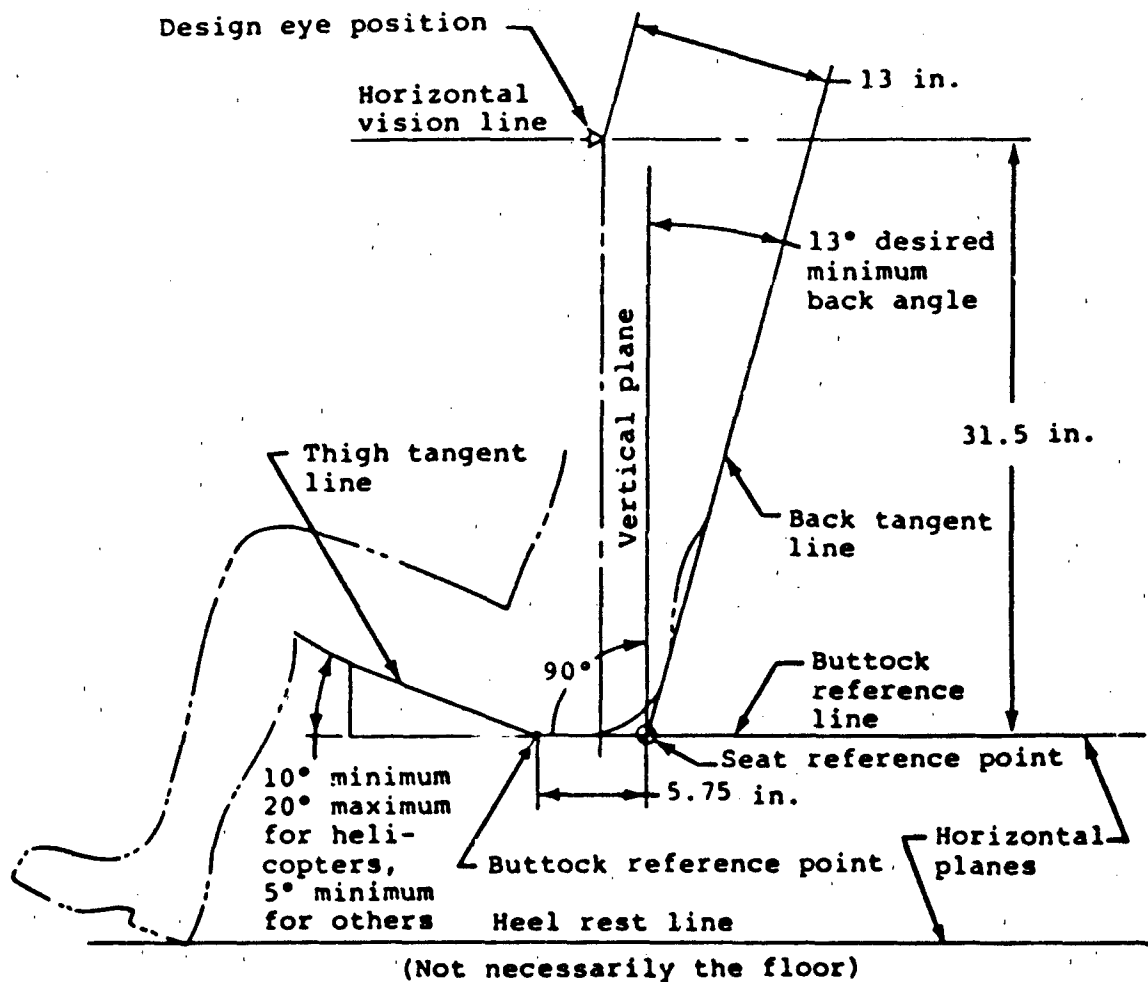
Figure D-2.2 - Seating Geometry (From Army CSDG)

STRUCTURAL TERMS

Airframe Structural Crashworthiness — The ability of an airframe structure to maintain a protective shell around occupants during a crash and to minimize magnitudes of accelerations applied to the occupiable portion of the aircraft during crash impacts.

Structural Integrity — The ability of a structure to sustain crash loads without collapse, failure, or deformation of sufficient magnitude to cause injury to personnel, or prevent the structure from performing as intended.

Static Strength — The maximum static load that can be sustained by a structure, often expressed as a load factor in terms of G.

Strain — The ratio of change in length to the original length of a loaded component.

Collapse — Plastic deformation of structure to the point of loss of useful load carrying ability. Although normally considered detrimental, in certain cases collapse can progress in a controlled fashion, maintaining structural integrity.

Limit Load — In a structure, limit load refers to the load the structure will carry before yielding. Similarly, in an energy-absorbing device it represents the load at which the device deforms in performing its function.

Load Limiter, Load-Limiting Device, or Energy Absorber — These are interchangeable names of devices used to limit the load in a structure to a preselected value. These devices absorb energy by providing a resistive force applied over a deformation distance without significant elastic rebound.

Bottoming — The exhaustion of available stroking distance accompanied by an increase in force, e.g., a seat stroking in the vertical direction exhausts the available distance and impacts the floor.

3.0 AIRCRAFT CRASH INFORMATION

Authors of the present edition of the U.S. Army's Aircraft Crash Survival Design Guide recognize and accept that trade-offs must be accomplished relative to earlier stated criteria. New generation Army aircraft are being procurred with stringent crashworthiness requirements, based on "95th percentile survivable accidents" as defined in an earlier study (ref. D-5). The new Guide emphasizes that component changes recommended by earlier editions, or those that might be implemented in attempts to resolve more specific problems, may not meaningfully improve crashworthiness in some fixed system designs. Accordingly, the authors point out that retrofit improvements are limited and may result in prohibitive weight and cost penalties if requirements are too severe or too rigidly applied, although some retrofit packages are feasible. Individual technological appraisals become necessary.

Army aircraft for which this present Army study was intended include rotary wing and fixed wing aircraft under 12,500 pounds, the small rigid body aircraft used in the Army mission. These aircraft are relatively unyielding during crash impact unless specific design provisions are incorporated. Anything exceeding the equivalent of a free fall of 100 ft in any of these aircraft is considered to be nonsurvivable. Resulting aircraft-related criteria are based on design factors that might be applied to such aircraft in order to reduce the degree to which human tolerance criteria might be approached, and thus improve survivability.

Human tolerance in the crash environment is the basic criterion for crashworthiness, and is related to acceleration magnitude, duration and rate of change. Crash environment data discussed in the Guide and herein relates information on factors that can be used to enhance this environment. Other factors influencing survival are:

1. Structural collapse, from impact or supporting large mass during impact

2. Structural elastic deformation

3. Structural penetration

4. Structural strength protecting egress operation

5. Structural strength of landing gear and seat restraint support system

COMMENT: Three different survivability goals are indicated or inferred in the new Guide. One is to eliminate "unnecessary" injuries and fatalities in relatively "mild" impacts. A second is to design "for the limits of human tolerance"...to maintain conditions at or below their tolerable levels to enable the occupant to survive the given crash environment. A third is implied, to survive any crash and be "combat ready."

BACKGROUND DISCUSSION

The Army approach to improving survivability has been in two stages, first by improving the "crashworthiness" of existing aircraft as practicable, then by influencing design of new aircraft through assuring consideration of improved capabilities. Army objectives for their "crashworthy" aircraft relate to minimizing injuries and fatalities and controlling structural damage so that "a survivable environment is more likely to be maintained." Army criteria were related to combat goals, in order to produce a positive morale factor and improve combat effectiveness. The army accordingly gives great emphasis and apparently considerable funding to maximize protection afforded to occupants by each subsystem without really addressing what minimum requirements

might be. In providing maximum protection as the authors of the updated Army Guide see it, a vertical crash impact is a series of energy absorbing strokes that occur as different ductile components yield. They use landing gear stroking to absorb a significant amount of energy; the fuselage contributes to absorption and provides a protective shell for occupants; the floor, seat, and restraint systems contain occupants within the shell and provide additional energy absorption to reduce occupant decelerative loading. Additionally, weapon sights, cyclic controls, glareshields, instrument panels, armor, and structure are to be delethalized.

COMMENT: The authors of the new Army Guide do not follow the more common engineering practice of allowing a cumulative system credit based on a summation of capabilities for components to some minimum requirement goal for energy absorption. Instead, they emphasize maximum protection possible from each subsystem, taking the position that it is not possible to simply specify human tolerance and vehicle crash conditions. For example, they take the position that designers must also consider probable crash conditions wherein all subsystems cannot perform their desired functions; e.g., no landing gear absorption of impact energy, since helicopters may not contact the ground via the landing gear. Criterion levels that are actually oriented to maximum possible performance are thus also recommended in the Guide for each individual subsystem, e.g., in energy absorption requirements for seat and restraint systems.

This amounts to extremely conservative engineering practice, since cumulative capabilities are accepted standard practice and since most design criteria are based on specifying minimum, not maximum, requirements. Opinions, practicality, and even estimates of feasibility will vary, creating a difficult-to-impossible situation. Secondly, design goals are not usually specified or accepted as a design practice. Additionally, the practice of generalizing from the worst case for one system to other aircraft that seldom, if ever, encounter that case is hard to justify (e.g., generalizing vertical loading criteria from upside down landing of a helicopter, or using helicopter based impact loads that are due to rotor thrashing, to set criteria for fixed wing aircraft with their vastly different impact circumstances).

AIRCRAFT CRASH ENVIRONMENT

Statistical studies were conducted to determine impact conditions for rotary wing and light fixed wing aircraft of mission gross weight no greater than 12,500 pounds during the period 1960 through 1965, and 1971 through 1976 (Volume III) (also ref. 6). Cases selected had at least one survivor and one or more of the following factors: (1) substantial structural damage, (2) postcrash fire, (3) personnel injuries. Numerous severe accidents were excluded from consideration, such as midair collisions or free fall drops of 100 ft or more because, "Such accidents almost invariably result in random, unpredictable crash kinematics and nonsurvivable impact forces, and are of little value in establishing realistic crash survival envelopes that would be useful to the aircraft designer."

COMMENT: In view of typical impact speeds compared to helicopters and light aircraft, most large commercial aircraft accidents may fall in this high load category.

Impact conditions were found to be similar from rotary wing to light fixed wing STOL aircraft, and, except for lateral conditions, were treated as being the same. Impact velocities were "known" for what appears to be a somewhat arbitrarily selected sample of 40 aircraft out of 600+ accidents that were reviewed (with errors in estimated impact velocity "probably" not exceeding ±20%), but could not be established for other aircraft crashes. One half the vehicles that could be appraised were estimated to experience a vertical velocity change of 24 ft/sec or less (equivalent to free fall of 8 ft, 11 in.), and 95% were estimated to experience a vertical velocity change of 42 ft/sec or less (equivalent to free fall of 27 ft 5 in.). Longitudinal velocity changes were approximately 28 ft/sec for the 50th percentile and 50 ft/sec for the 95th percentile crash.

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Impact accelerations were estimated by the original accident investigation board and recalculated by the survey team. Additional analysis was performed for cases that "appeared to be near the upper limits of survivability." The 40 aircraft used were selected from an overall review that covered 563 rotary wing and 92 fixed wing aircraft, of which 373 were used to establish impact conditions. Impact attitudes were also used from the added collection of crash data for 108 attack helicopters and 10 cargo helicopters for the period 1971 to 1976. The statistically most frequent impact involved trees. It was found that loose soil could be beneficial, or alternatively could actually increase decelerations (e.g., if the structure dug into the ground).

Since insufficient lateral data were available, lateral velocity changes were inferred from circumstances of the helicopter and light aircraft accidents to be 25 ft/sec, supplemented by recent studies suggesting 30 ft/sec. Based on the above the three-dimensional resultant for velocity changes did not appear to exceed 50 ft/sec, although vector summing is specifically identified as inappropriate.

Floor decelerations were estimated from the following equation; however, this may well overestimate G_{ave} if the peak in fact occurs early in the pulse (see appendix D-A, fig. 1).

$$G_{ave} = \frac{V^2}{2gs}$$

Overall, the authors concluded that 95% of the "survivable" helicopter and light fixed wing aircraft accidents involved average vertical accelerations of less than 24 G (with "peak" accelerations of 48 G, assuming triangular pulse shape). Average longitudinal accelerations were 15 G and average lateral accelerations were 16 G (most particularly during auto rotation into trees, fuselage rotation, then landing on the side). Actually, most accidents occurred with small yaw and roll angles.

Accidents involving postcrash fire were considered where possible, but burn damage in many accidents precluded analysis of impact forces. Still others provided insufficient or inadequate data for detailed case analysis.

Earlier impact criteria used by Army were based on an early decision to increase crash survivability that appears to have been somewhat arbitrary (Army Crash Survival Design Guide, first and second editior) to a level based on a study in the 1960 to 1965 time period (Haley, ref. D-6) which defined a survivable crash as any crash with at least one survivor, and setting objectives for Army aircraft to the 95th percentile loads for such conditions. The authors of the new Guide emphasize that, now that serious attempts to meet the criteria have been incorporated to some extent in a number of Army aircraft, it would be a mistake to continue using a floating baseline (i.e., the 95th percentile crash) since it could only lead to a never-ending increase in crashworthiness at the expense of aircraft performance. Accordingly, the 95th percentile criteria is dropped in the new Guide and the design pulse derived in the earlier effort continues to be recommended for Army use (figure D-3.1).

COMMENT: The rationale for selecting only 40 aircraft for the sample analysis not totally clear. There is a reasonable likelihood that many of the cases that were, accordingly, not included in the study could very well have been more mild but were not survived for some other reason than deceleration, such as fire. Additionally, much is based on the very conservative case of a 95th percentile accident; however, data reported within the Guide suggest a factor of 2+ in magnitude between the 90th and the 95th percentile accident, which varies considerably from the normal magnitude of the true statistical difference between 90th and 95 percentile (a 20% change rather than a 200% change). There is no clear justification for the 90th or 95th percentile survivability goal to be adopted, other than as an arbitrary goal for which the degree of feasibility remains to be determined.
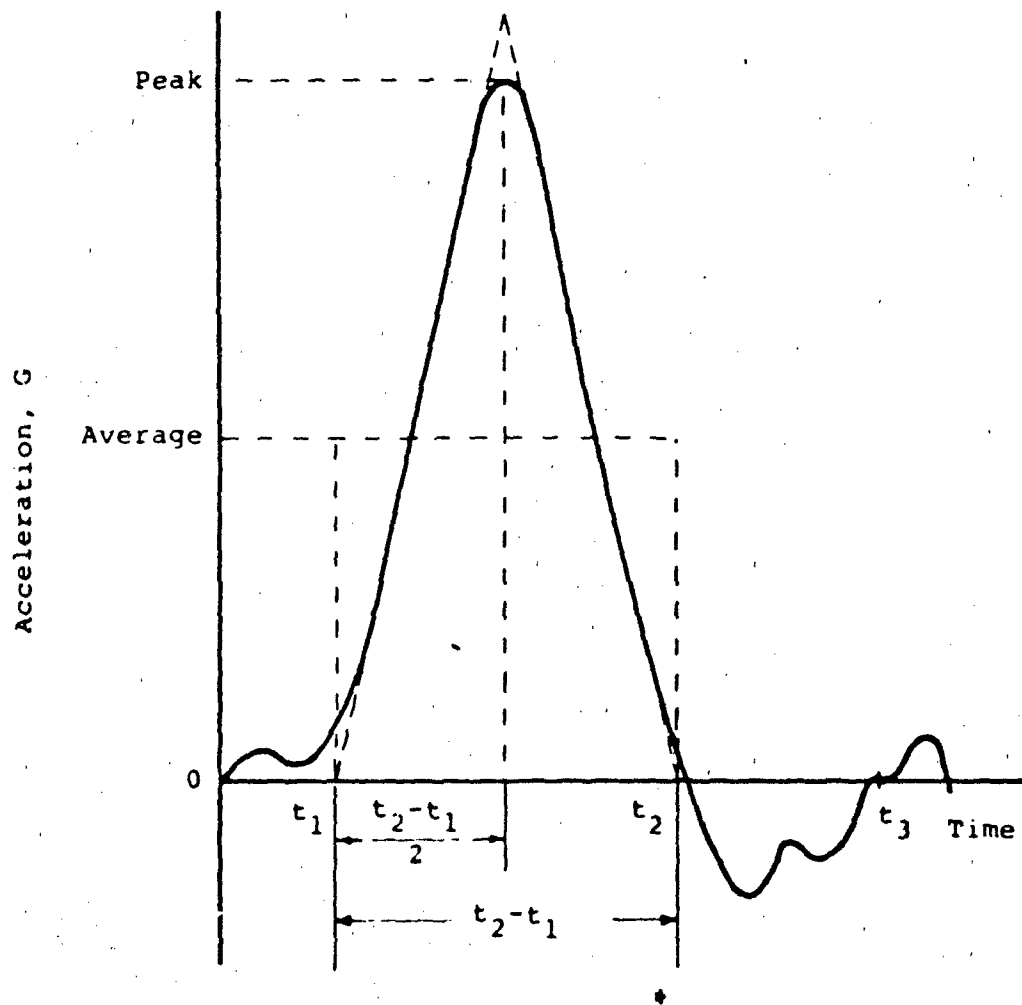
Figure D-3.1 – Typical Aircraft Floor Acceleration Pulse (From Army CSDG)

OH-6

OH-58

AH-1

YAH-64

Side elevations of typical U. S. Army observation and attack helicopters.

UH-1

UH-60

CH-47

CH-54

Side elevations of typical U. S. Army utility and cargo helicopters.

TH-55

Side elevation of typical U. S. Army training helicopter.
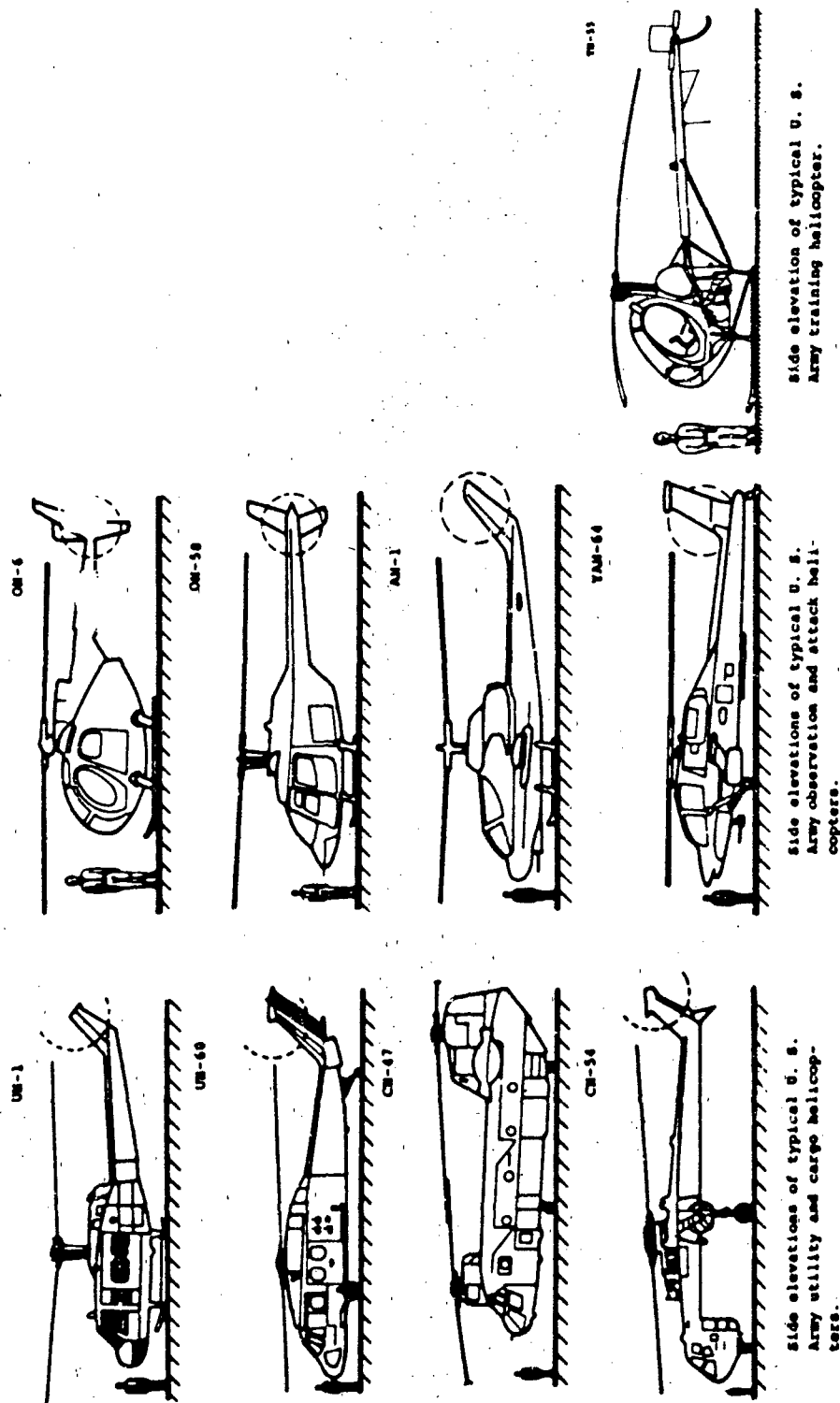
Figure D-3.2 – Army Helicopters (From Army CSDG)

The 95th percentile objective was apparently adopted as such an arbitrary objective for the Army, which has the option to set goals and determine feasibility in a specific design context, and then also has the authority to waive those elements that are not considered feasible and practical within the context of Army needs.

Continued Comment: Now, after several years experience, the general approach and commentary presented by present authors suggest that the "criteria" are really guidelines and goals from which practical trade-offs must be made. Additionally, the exclusion of certain types of severe accidents causes no problems for the analysis of light aircraft crashes for Army purposes and given their freedom to waive guidelines. A light aircraft accident of sufficient severity to have "random, unprectible crash kinematics" would rarely have a survivor. This is not true in the commercial environment. Because of the size and inherent energy absorption from body flexing of a large commercial aircraft, crash forces to which the occupants are exposed can vary considerably through the aircraft. It is not uncommon for there to be a few survivors even in a severe accident at flight speeds and with "unpredictable crash kinematics." Thus the methodology for establishing crash load criteria developed in the Guide should not be applied to commercial aircraft.

AIRFRAME STRUCTURAL CRASHWORTHINESS

In the updated Guide, discussion starts with the basic requirements for survival, i.e., a protective structural envelope and the attenuation of impact forces. Basic design goals/requirements are also stated, recognizing that improvements may be feasible but using qualitative terms in recognition that achievements will be limited.

AIRFRAME CRASHWORTHINESS

General Design Considerations—The U.S. Army's Aircraft Crash Survival Design Guide appears to be specifically intended to define criteria for vehicles designed to support the Army capability "to conduct prompt and sustained combat incident to operations on land." All the combat ground-support functions described involve the potential of exposure to enemy fire while at some nominal altitude, i.e.:

1.   Command, control and communications

2.   Intelligence

3.   Mobility

4.   Fire power

5.   Combat service support

The Army inventory includes both helicopter and fixed-wing aircraft. The maximum capacity of any listed aircraft is a crew of 2, with 20 passengers. The helicopter inventory used for such purposes includes (figure D-3.2):

1.   Observation (OH)

2.   Attack (AH)

3.   Utility (UH)

4.   Cargo (CH)

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5. Training (TH) (with its own special cases)

Fixed-wing aircraft include (figure 3.3)

1. U-*0

2. U-3

3. U-21

4. U-8

5. C-12

6. UV-18

7. OV-1

However, the authors suggest that information presented in the airframe structural crashworthiness volume (Volume III) applies to any light aircraft.

They qualify this in the same paragraph, in a statement that the impact environment is similar for all types of existing light fixed-wing and rotary-wing aircraft except for lateral impact. Lateral impact levels for cargo and attack helicopters are said to compare to light fixed wing aircraft, and other helicopters experience a more severe lateral impact environment.

The authors go on to state that experience and reason indicate that there will continue to be accidents that threaten occupant survival. However, their position is "acceptable aircraft structures should always provide the greatest possible degree of occupant protection from crash conditions. All available information should be considered ... to ensure that new designs will be 'acceptably' crashworthy." They consider desirable conditions to include multiple load paths to keep the structure intact in spite of localized damage. However, they recognize that excessively strong structure does not necessarily meet this objective; in the nonyielding modes, it will contribute high acceleration and involve both weight penalties and energy absorption constraints.

The 95th percentile design load limits based on severe crash accelerations in this guide set several new criteria compared to the earlier version; they also tend to shift the emphasis from peak accelerations to average accelerations. Their requirements (for a severe crash) compared to FAA requirements for a minor crash are shown in figures D-3.4 and D-3.5.

Impact conditions may include:

Helicopter

1. Vertical impact from power failure during low power maneuver at low altitude

2. Inverted impact (and other impact attitudes) following rotor contact with wires, trees, etc.

Light fixed-wing

1. Vertical impact with stall near ground

C-12

UV-18

OV-1

(contd). Side elevations of typical U. S. Army
fixed-wing aircraft.

U-10

U-3

U-21

U-8

Side elevations of typical U. S. Army
fixed-wing aircraft.
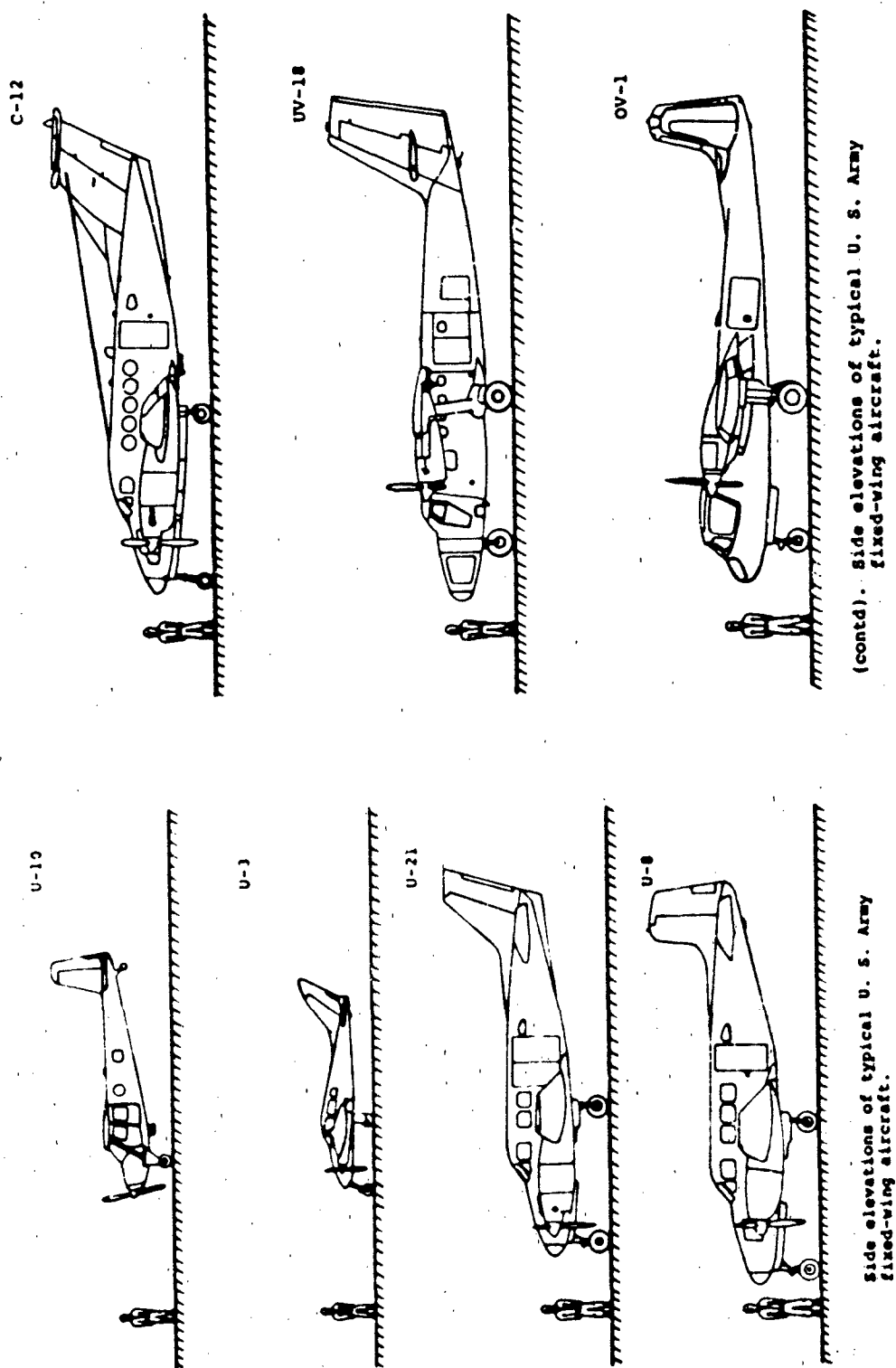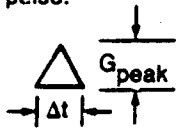
Figure D-3.3 – U.S. Army Fixed-Wing Light Aircraft (From Army CSDG)

Impact direction (aircraft axes)	Velocity change, Δv (ft/sec)	Acceleration Peak (G)	Average (G)	Pulse duration, Δt (sec)	Comments
Longitudinal (Cockpit)	50			0.104	Triangular deceleration pulse:
Longitudinal (Cabin)	50			0.130	
Vertical	42			0.054	
Lateral	25[a] 30[b]			0.097 0.104	Δt calculated from known or assumed values for G_{peak} and Δv: $$\Delta t = \frac{2(\Delta v)}{g\, G_{peak}}$$

a) Light fixed-wing aircraft, attack and cargo helicopters.
b) Other helicopters.

Figure D-3.4 – Summary of Crash Impact Conditions for Helicopters and Light Fixed-Wing Aircraft Design

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Compared to the figure 3.4 data, commercial aircraft size certified according
to FAR PART 25.561, Emergency Landing Conditions, Para (b) which requires that

> "...the structure be designed to give each occupant every reasonable
> chance of escaping serious injury in a minor crash landing when

> (1) proper use is made of seats, belts and all other safety
>   design provisions;

> (2) the wheels are retracted (where applicable);

> and

> (3) the occupant experiences the following ultimate inertia
>   forces acting separately relative to the surrounding structure:

>   (i)   upward 2.0g
>   (ii)   forward 9.0g
>   (iii) sideward 1.5g
>   (iv)   downward 4.5g or any lesser force that will not
>   be exceeded when the airplane absorbs the landing
>   loads resulting from impact with an ultimate descent
>   velocity of five f.p.s. at design landing weight."

Vertical loading to 6.0g for a type I (transport) seat was later
imposed to accommodate gust loads (Technical Standard Order TSO 37.136,
Aircraft Seats and Berths, TSO C39a; and National Aircraft Standard
(NAS) 809, Specification-Aircraft Seats and Berths, January 1, 1959).
3g cargo nets are used, which are also cited in the Guide as used
by the U.S. Air Force in the USAF 463C pallet system with "statistically
rare likelihood of causing injury."

==

Figure D-3.5 – FAR Part 25 Criteria

2. Longitudinal impact with obstacles, (e.g., mountains, ground obstacles) or nose down diving attitude

3. Cartwheeling

Secondary impacts such as hitting a ridge after the initial crash are "generally less severe for occupants." Hazards from detached components (e.g., engines), penetration (e.g., by tre s), and fire and water become more severe.

STRUCTURAL DAMAGE

In the Guide's discussions of helicopter and light fixed-wing aircraft crashes, it is stated. ..."The structural damage that produces occupant injury is generally the same for both types of aircraft. Structural damage in severe accidents cannot be avoided. However, improvements in airframe structure and optimization of element distribution can work to control the manner in which structural damage occurs so that a survivable environment is more likely to be maintained."

The structural scenario is one of localized deformation at contact until kinetic energy is absorbed over a relatively long stopping distance or until enough structure is involved to produce a significantly shorter and higher deceleration force. Likelihood of damage increases with build up of large decelerative forces, which may in turn cause aircraft buckling and compression of the protective cabin shell. Cabin deformation may be reduced by permitting parts to break free on impact; however, this may produce no significant reduction in impact loads.

Variations on this Army scenario of crash loads, direction and build-up include: (1) Longitudinal: deformation of forward areas in such a way as to form a scoop which picks up earth. Alternatively, the nose might roll under the aircraft. In more direct, head-on crashes into the ground, the nose generally deforms to destroy the occupied section. (2) Vertical: from high sink rate or roll-over which crushes occupiable volume, or transmits high vertical loads to the occupants. (Lateral roll-over occurs with helicopters). (3) Lateral impacts: from rotor actions or roll-over that relates to the high center of gravity with helicopters and from spin-in with light fixed wing aircraft. (4) Lateral or longitudinal: transverse bending loads may deform or rupture the shell; (5) Any of the crash scenarios may create floor buckling which may degrade integrity and strength of floor structure, or landing gear may penetrate the fuselage; and rupture of fuel or ignitable fuel containers is a frequent cause of fire.

DESIGN REQUIREMENTS — (GUIDELINES) GENERAL

According to Guide authors, "aircraft systems should be designed to prevent occupant fatalities and minimize the number and severity of occupant injuries to severities as were defined in figure D-3.4 to the maximum extent practical." Areas cited for attention include:

1. Deformation of airframe protective shell in a controlled, predictable manner to minimize forces on occupants and maintain the protective shell, minimizing earth scooping, buckling, and failure loading of floor structure

2. Tiedown strength

3. Occupant acceleration environment

4. Occupant environment hazards

5. Postcrash hazards

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Stated (helicopter) impact criterion conditions are to ram a wall at 15 ft/sec longitudinally (similar to low speed automotive bumper test) with the aircrew to both survive and evacuate the cockpit, and with the airframe capable of longitudinal (front end contact) of 40 ft/sec without reducing the cabin compartment by more than 15%.

Guidelines include recommendations for sufficient strength to prevent bending or buckling failure, fuselage to buckle outward rather than inward, personnel to be positioned away from likely fuselage fracture/failures points, sufficiently strong structure provided around surrounding exits to assure postcrash operability, and cargo tiedowns included that will restrain cargo should fuselage bending failure occur. Other considerations are to avoid reducing the width of the occupied areas by more than 15%, or permitting either lateral collapse or structural intrusion of occupiable portions that would be hazardous to human life (including entrapment). Wings and empennage should fail outside the occupant protection area. Engine and (helicopter) transmission mounts should stay attached and avoid hazardous displacements. Helicopter rotor blades should not displace in a manner hazardous to occupants during rollover in roll or pitch (on sod), or from the force generated by strikes by the outer 10% of rotor span on an 8-in. diameter rigid cylinder. Failure of the landing gear should not result in failure of seats, restraint systems, or tiedowns. Load limiter attention is suggested, to contain loads to less than those produced by 20 ft/sec vertical impact velocity.

COMMENT: These goals offer no particular problem as guidelines. However, it is very likely nearly impossible to assure that such objectives can be met in advance or have been met after the fact.

ANCILLARY EQUIPMENT RETENTION

Retention of ancillary equipment at criterion loads is "required." Load limiting devices should minimize the likelihood of equipment to enter an occupant strike envelope. Stowage should provide easy view of the area and easy, reliable accessibility in a way that cargo shifting or fuselage distortion will not prevent access. Single motion, five-second removal should be provided. Stowage space for nonrestrained items that are not regularly carried aboard an aircraft should be provided in all aircraft. This space should be located so that the items stored in it cannot become hazardous to personnel in a survivable crash.

Ancillary equipment includes:

1. Emergency equipment
   Oxygen bottles
   Fire extinguishers
   First aid kits
   Portable searchlights
   Crash axes

2. Survival equipment
   Survival kits
   Life jackets
   Locator beacons
   Special clothing
   Food and water

3. Subcomponents
   Panel-type consoles containing control circuitry
   Radio and electronic equipment
   Auxiliary power units

Batteries
Special equipment

4. Miscellaneous equipment
    Navigation kits
    Briefcases
    Log books
    Flashlights
    Luggage
    Toolboxes

INTERFACE OF RETENTION SYSTEMS WITH AIRFRAME, AND CARGO RETENTION

Occupant retention should ensure that occupants are retained in precrash positions during cited crash loads. Additionally, occupant/cargo retention systems that interface with airframe and cargo restraint should utilize tie points that are integral to the frame. Loads should be evenly distributed and tie downs should handle loads at the worst case angle without yielding. Load limiters should be used when structure of fuselage and floor is not strong enough to handle cargo crash loads. However, nets used to restrain small cargo should feature low elongation characteristics in order to reduce travel to a minimum. Army Guide cargo load criteria are 16 G peak (8 G_{ave}) with a longitudinal velocity change of 43 ft/sec in contrast to the USAF successful experience with 3 g systems — USAF 463c pallet systems. When cargo is stowed behind the passengers... "lower criteria (90th percentile pulse) are acceptable since a net designed for a given load would be loaded to a lower value in most accidents,"; by the same reasoning lateral restraint with a load limiter is called out as 10 G (peak, triangular; 5 G_{ave}) and 21 ft/sec from a 90th percentile crash.

More specific factors in retention include:

1. Crew and passenger locations relative to cargo

2. Type of aircraft

3. Likely crash modes versus tiedown back up structure (simplest, most effective tiedown should be used)

4. Type of cargo restraint criteria, aircraft response to crash load an . clearance envelopes

5. Aircraft and cargo tiedown provisions

6. Cargo/personnel clearance envelopes

7. Type of restraint devices available (and potential for deterioration)

Cargo restraint load limiters are recommended by the authors of the Army Guide, to maintain load level and control physical motion of shifting cargo to space not occupied by personnel. A buffer spacing is recommended for personnel aft of the cargo, to allow for restraint system elasticity (for cargo restraint with a 5 G rebound load). Additionally, combining restraint devices of differing elasticity and yield points of cable, rope, strap, or chain should be considered since premature failure of stiffer devices may set off a chain reaction. Guide authors indicate practical limits of displacement are a significant factor in related trade-offs, but tiedown design loads may also be important. Although the goal does not appear to be specifically related to personnel safety, the Army Guide authors recommend design of the cargo floor for 16 G down-loading (peak or average not stated). Additionally, protection against forward and lateral displacement requirements, as well as down and up are not defined since they are not considered to be as potentially hazardous.

COMMENT: The resulting Army recommendations for load limit factors are included in figure D-3.6 which appears to represent some kind of a two-way limit on dynamic and static loading. These curves are used by the U.S. Army, but have not been justified as a new basis for setting criteria. Compared to USAF and FAA commercial 3 G netting restraint criteria discussed earlier, these criteria are quite conservative. Additionally, the dramatic change in load level criteria as the "survivable" crash changes from the 95th percentile to the 90th percentile is puzzling. Results indicate that this may not be true statistical sample. To say the least, it is unusual for a change amounting to a factor of 2 to occur in this percentile spread regardless of the parameter (or, in other words, accounting for 50% of the total range).

AIRFRAME PRINCIPLES AND CONCEPTS

Authors of the Guide take the position that certain criteria are applicable whether results are approximate or precise:

1. Structure surrounding occupiable area must remain reasonably intact, without significantly reducing space. Otherwise other "efforts to improve survivability ... are futile."

2. Ideally, "structure should minimize occupant accelerations to survivable levels in a severe crash environment while maintaining the required survivable volume, retaining large mass items, interior equipment, seats and cargo," and considering effects from roll over, cabin penetration, etc.

By U.S. Army philosophy, aircraft structure should first be designed for normal loads, operations, performance, space, fatigue life, etc., then secondly to handle normal payload conditions. Then "the effects of crash loads must be considered to determine where structural modifications are needed to improve crashworthiness."

COMMENT: This reinforces earlier conclusions of the present critique, that the new Guide gives greater emphasis to practical improvements for safety and survivability purposes after basic mission design is completed.

FUSELAGE CONSIDERATIONS

Design of the fuselage can control both the degree of collapse and the level of acceleration experienced by occupants during a crash. On the one hand, selected regions can be designed to withstand greater forces without collapse. On the other hand, deformation and collapse of other structure in unoccupied regions can be used to improve energy absorption potential. Other variables and trade-offs to be considered include the following related U.S. Army design concepts. However, design considerations listed below may not be applicable to commercial jet aircraft. For example, operating speeds for large commercial aircraft hardly make survival of a 30° impact at 130 kn landing speeds a likely outcome; this is not unlike the evaluation by Guide authors of 100 ft free fall as unsurvivable.

Related U.S. Army Design Concepts

Longitudinal Impact

1. Methods of reduced earth scooping for longitudinal impact, including deformation control and use of the overlap from shingling of joints in skin to prevent skin deformation leading to scooping of earth.

2. Impact angles up to 30°, including the rapid change in pitch angle to realign the fuselage with the impact surface, and associated
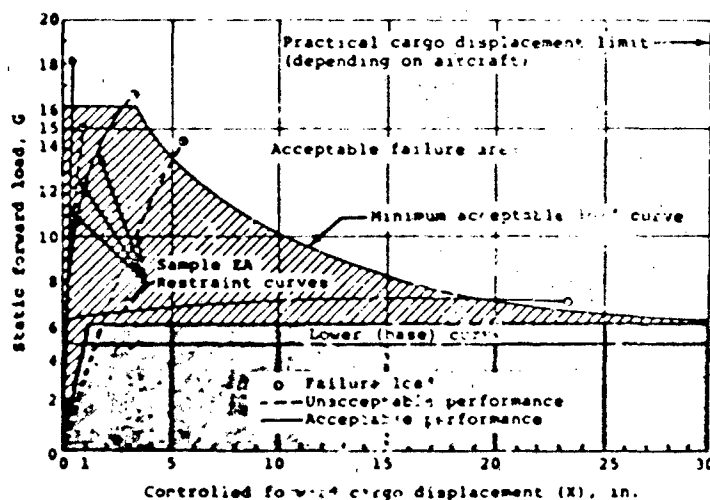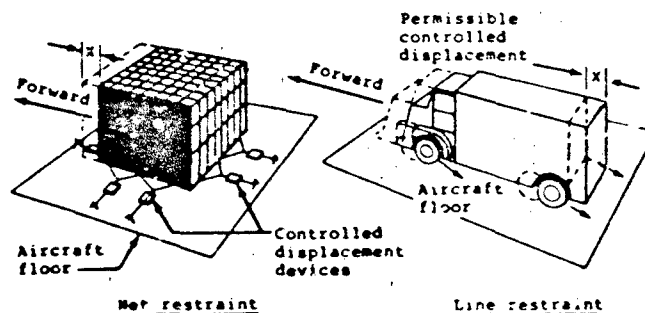
Figure D-3.6 – Load Displacement Requirement for Cargo Restraints (From Army CSDG)

- Fuselage bending failure

- Effects on floor structure

- Decrease in occupant volume

Vertical Impact

1. More limited energy absorption stroke

  - Shorter distance, fewer trade-off models

  - Energy absorption strokes can include:

    - Gear

    - Fuselage

    - Floor

    - Seat

    - Cushion

2. Control of conditions for vertical collapse

  - Dissipation of energy according to where the mass is concentrated.

  - Structural design to control both elastic (recovering) and plastic (deforming) energy absorption and for cabin integrity design to enhance absorption below floor level

Lateral Impact and Rollover Protection, from:

1. Design of butt line beams, longitudinal floor beams, and main box frames

2. Preventing intrusion by rotor blade and other external members

Other:

1. Energy absorption by incremental rotor whipping and failure, or by wing loading and failure (wings can absorb up to 5 G)

2. Breakaway wing fuel tanks

3. Engine mounts keeping engines (helicopter and front located fixed/wing) attached to basic structural member

4. Rigid emergency exit structure to prevent deforming (to withstand at least a 5 G load)

5. Emergency exit access for rapid egress

6. Fuel Tanks

- Maximum possible distance to occupiable areas

- Away from probable ignition sources so much as feasible; (engine compartment, battery, other primary ignition sources)

- Away from probable impact damage, e.g., landing gear penetration

- Controlled, tank structural deformation, e.g., by regular structural shape to minimize deformation pressure

- Fuel cell supports to deform without tearing

Materials and Structural Properties

Material contributions to controlled collapse for failure modes of metallic, nonmetallic and composite materials include:

1. Controlled collapse mechanisms

2. Material failure modes that do not produce projectiles

3. Joint designs and fastener selections that control failure mechanisms and minimize the formation of projectiles

Applications of material properties for crashworthiness include absorption of energy through structural deformation, degree of protective shell distortion/retention for the occupiable section, use of surrounding structure as a buffer, and occupant protective devices. Material ductility helps to ensure that crushing, twisting and buckling can occur without rupture. Nonsparking material on impact surfaces helps to reduce post crash fire hazard.

Examples of controlled failure modes include:

1. Minimize inward buckling structures, such as sidewalls, bulkheads, and floors.

2. Use deforming joints and attachment fittings to control failure modes.

3. Minimize materials that suddenly unload with brittle fractures, causing additional impulse effects and potentially progressive failures in adjacent structures.

4. Minimize failures of members that result in penetration by jagged ends into occupied space or fuel cells, or by failed structure or exterior agents.

5. Avoid excessive distortion of emergency exit surrounds that might constrain the postcrash opening of doors or windows.

6. Protect flammable fluid containers from penetration

Some of the new materials characteristics and trade-offs that are already recognized are:

1. Structural designs may also contribute to controlled deformation.

2. Composites save weight, but have different strength versus ductility properties. Additional energy absorbing material in strategic areas may become necessary. Selected energy and load limiting absorbing concepts from the Guide are presented in figures D-3.7 and D-3.8.

3. Alternatively, filler materials such as honeycomb and structural foams may achieve adequate energy absorbing performance. However, mission requirements may limit use.

4. Thermal mismatch of new materials may become a problem from unequal expansion and contraction due to normal temperature changes. Representative characteristics are provided in the Guide.

Controlled deformation for helicopters can permit full use of the landing gear in a vertical stroke for some impact modes. Use of landing gear for energy absorption offers, potentially, a large absorption factor for vertical loads (e.g., an 18-in. stroke, 18.25 G peak, 9.125 G_{ave}, load limited gear at 100% efficiency would totally absorb a 42 ft/sec impact velocity). However, little advantage from landing gear failure is suggested for longitudinal impact — at 160 mph, landing gear failure is suggested by the Guide to absorb only 1% of the kinetic energy. Additionally, avoiding hazards from gear failure is identified as a significant problem; the recommendation is a design that keeps the gear away from the fuselage or from flammable fluids, or even sets up the gear to be carried away on impact.

COMMENT: Distinctions in operations and design on the one hand and in inherent structural flexibility and ductility on the other hand, when comparing large flexible body aircraft to the rigid body small aircraft, will make a great deal of difference in both the type, quality, and degree to which the above structural features might be beneficial. For example, landing gear are specifically identified as a potentially large energy absorber in the rigid-body aircraft for low speed vertical impacts, but offer little energy absorption at "high" speed horizontal impacts that approximate stall speeds for large commercial transports. Also, landing gear location and the conditions of impact offer a different situation so far as gear failure is concerned. Guidelines regarding nonintrusion are similar to existing FAA requirements, e.g., nonintrusion of gear into the electrical and fuel systems when the gear fails.

Accordingly, this section of the Guide offered a number of guidelines and qualifications that bear consideration in design. However, quoted criteria levels cannot be applied to commercial aircraft unless research can establish levels appropriate to large flexible-body aircraft.

EVALUATION TECHNIQUES

ANALYTICAL METHODS

Simulation may be by analytical models, scale models, computer models and full-scale tests in order to provide both observation of complex interactions and a rational basis for the sequencing of events, loads and modes of failure. Volume III of the Guide presents a major section on the basic elements of some of these methods. They will not be abstracted here.

As outlined in the Guide, numerous computer simulation models in particular are being developed for use in simulation evaluations. Some are being developed for support of preliminary design studies; others for more sophisticated uses. The five main classes of models that are used include:

1. Simplified spring mass models

2. Generalized spring mass models

3. Hybrid models
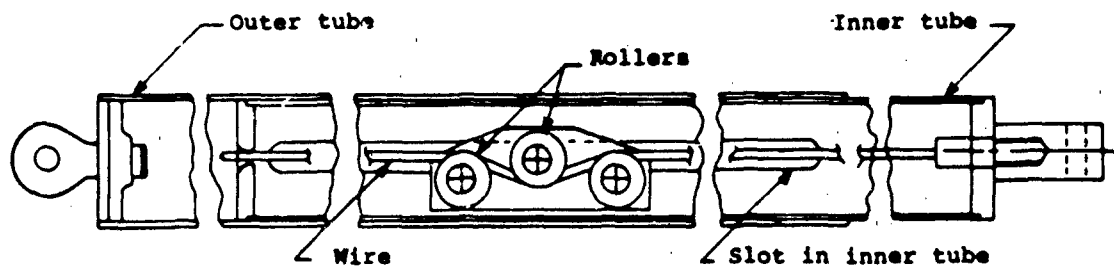
(a) Wire bending - absorbs energy by plastic bending
    of wire over rollers
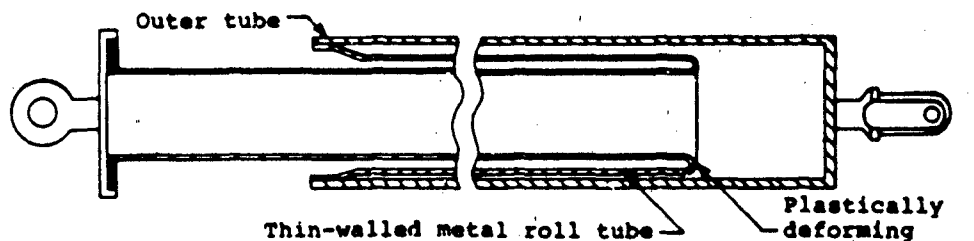
(b) Inversion tube - absorbs energy by inverting
    a thin-walled tube
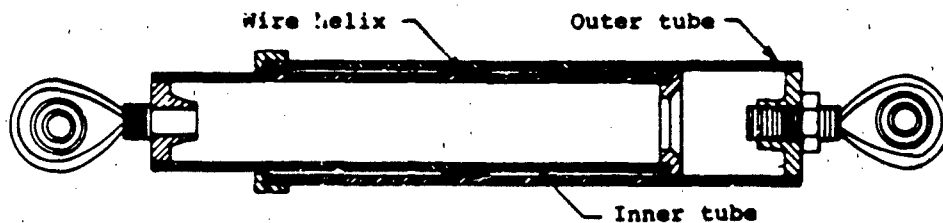
(c) Rolling torus - absorbs energy by rolling wire
    helix between concentric tubes

(d) Tension pulley - absorbs energy
    by plastic spreading of the
    pulley housing
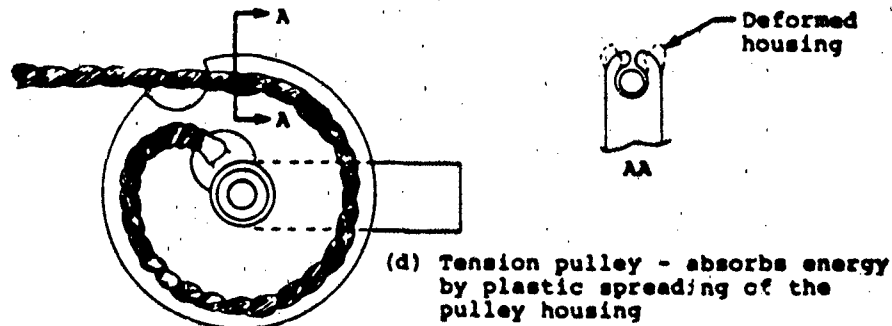
Figure D-3.7 – Examples of Energy Absorbing Devices (From Army CSDG)

Kevlar straps maintain
structural integrity
and react side loads

Foam-filled Kevlar
tubes provide
vertical and
lateral energy
absorption

30° impact

Vertical impact

Corrugated Kevlar
semi-tube provides
vertical and lateral
energy absorption

No foam in center
section for controls
routing

Outer tubes may be
foam filled for an
additional absorption
capability

30° impact

Vertical impact

Filament-wound sandwich
double-tube substructure
around crushable core provides
vertical and lateral energy absorption

Honeycomb or
foam provides
additional
vertical and
lateral energy
absorption

Vertical impact   30° impact

Beams and bulkheads must
provide progressive collapse
and energy absorption and
react vertical, longitudinal,
and lateral impact loads
(structural floor removed)

Stiffen
skins by
adding
plies

Most dense
core or
foam

Dense
core

Kevlar
face
sheet

Foam or
balsa
core

Least dense
foam or core

Less stiff
skins

Frangible
corrugated
core

Energy-absorption concepts - beams and bulkheads
(vertical impact). (From Reference 23)

Figure D-3.8 - Sample of Energy Absorbing Concepts (From Army CSDG)

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4. Frame type models

5. Finite-element models

The first two classes differ in level of detail. Frame type models use beam elements instead of spring elements and lumped or rigid body masses at beam element intersections. They may be two-dimensional or three-dimensional. Hybrid models require static component tests to obtain mechanical properties of structure. The finite-element approach uses more formal approximation approaches for more discrete definition of structural representation and properties. Finite-element models tend toward increasing complexity and computational cost. However, none of the modeling procedures is totally free of testing requirements and analytical judgment. The reason is the extremely complex process for vehicle structure deformation under crash loading, which involves:

1. Transient, dynamic behavior

2. Complicated framework and shell assemblies

3. Large deflections and rotations

4. Extensive plastic deformations

COMPUTERIZED METHODS OF ANALYSIS (State-Of-The-Art Summary, Not From Guide)

Impact dynamics of a real crash involving complicated structural design are too complex for manual analysis; however, modeling methods offer an eventual capability that could provide a simulation of all the dynamic interactions. For example, numerous dynamic models of the human body have been developed for crash impact analysis to predict the response of the occupant, restraint and/or seat systems.

One-, two-, and three-dimensional models have been developed. More broadly described in this present report are:

1. Dynamic Response Index (DRI) (ref. D-5)

2. SOM-LA (Seat Occupant Model: Light Aircraft) (ref. D-7)

3. PROMETHEUS (now PROMETHEUS III, two-dimensional mode with restraint performance integrated with body dynamics and other outputs similar to SOM-LA) (ref. D-8).

Occupant Modeling Summary

Three occupant-simulation computer programs are evaluated in following paragraph with regard to their ability to produce useful engineering trade-off data regarding relative safety of a restrained occupant: a one-dimensional model (DRI), a two-dimensional model (PROMETHEUS III) and a three-dimensional model (SOM-LA).

The one-dimensional (DRI) model is usable only for seat ejection evaluation and is of no use for evaluating the safety of commercial aircraft. The two-dimensional model (PROMETHEUS III) is suitable for producing sophisticated engineering trade-off data and is being used for this purpose, subject to the limitations imposed by the two-dimensional nature of the simulation. The three-dimensional model (SOM-LA) needs modeling improvements before being usable for engineering

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purposes. The needed improvements are technically difficult and fall into the realm of applied research. Although SOM-LA is not currently adequate for evaluation of restraint system performance, it provides a rough approximation of the gross motion of the occupant for purposes of obtaining the dynamic loads on the seat structure.

The possibility of merging these programs with a large finite-element computer program such as DYCAST is also considered and a procedure for accomplishing the merging is proposed.

Program Calibration

Computer modeling of transient structural dynamics is a relatively new technology, and standards defining what is a good structural dynamics computer program are still evolving. (Occupant-simulation is a special type of structural dynamics). As a consequence, each new structural dynamics computer program must individually earn acceptance in the engineering community before its calculations will be utilized by designers.

There are two aspects to acceptance. First, the program must produce believable results. That is, predicted dynamics should appear reasonable and credible to the designer and the designer should be confident that the program models the main dynamic effects. To enhance believability, the program output should contain, in readable form, information which assists the designer to understand the dynamic events (such as time-histories of system forces). Graphic aids are also helpful.

The second ingredient vital to engineering acceptance is demonstration of program accuracy. That is, demonstration of capability to reasonably predict an actual test. Achievement of predictive accuracy is usually a very difficult and time consuming process for occupant-simulation codes because of the nonlinear nature of the problem and the difficulty in obtaining measured values for dynamic parameters. The calibration of the PROMETHEUS III occupant-simulation computer program will be described to illustrate how this process might work.

Instrumentation data from several sled tests were obtained from the Federal Aviation Agencies Civil Aero Medical Institute (CAMI). Physical data for the anthropomorphic dummies were obtained (limb weights, measurements, spring constraints). Properties were estimated where measured data could not be found. One of the CAMI tests was then simulated by PROMETHEUS.

When the initial simulation did not provide satisfactory correlation with test data, the problem was attacked from two directions. First, it was evident that the restraint system model in PROMETHEUS was inadequate, so a more sophisticated mathematical model of the lap belt and shoulder harness was developed and added to PROMETHEUS. For example, the lap belt was refined to permit the slipping associated with submarining, the shoulder harness was refined and chest/shoulder flexibility was added to appropriately incorporate harness/body interactions and slipping of the harness on the shoulder.

The second approach, which was attempted concurrently with the first, was to parametically vary the mechanical properties of the simulated occupant (such as neck stiffness and damping) in PROMETHEUS simulations and note the resulting trends. The parametric variations helped provide a feel for the occupant dynamics and served as sensitivity studies to identify the important dynamic parameters. Some dynamic effects were observed which were not influenced by the parametric variations; additional modifications were made to the mathematical modeling in PROMETHEUS and parametric evaluations completed to approximate these effects. Additional cycles of modeling improvements/parametric variations continued until correlation with actual test data was achieved.

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The resulting modeling changes to PROMETHEUS were quite extensive; so much so that the correlated model was renamed PROMETHEUS III. Figure D-3.9 summarizes the parametric variations and modeling changes required to achieve calibration.

After calibration, an independent test case was simulated with PROMETHEUS, producing good agreement with actual test results involving a real Part 572 dummy in sled testing. Figure D-3.10 indicates the correlation finally achieved.

Review of Occupant Simulation Computer Programs

Three occupant-simulation models are reviewed in following paragraphs. These consist of a one-dimensional model (the spring-mass model associated with the Dynamic Response Index (DRI), and a comparison of a two-dimensional model (PROMETHEUS III) and, a three-dimensional model (SCM-LA).

The models are examined from two viewpoints — first, as a tool for engineering design of a seat/restraint system, and second as a possible candidate for integration into a large structural dynamics simulation computer program in order to model the complete system (aircraft, seat and occupant) in a single simulation.

One-Dimensional Model (DRI) — A one degree of freedom dynamic-response model of a human occupant has been proposed (ref. D-5). The model consists of a simple linear spring and damper, and a point mass. The spring is sized by the compressive stiffness of the lumbar vertebrae and the damper is sized by human vibration tests.

The DRI is an injury scale associated with this model. The DRI for a deceleration pulse is the ratio of the peak compressive spring force which occurs when the model is excited by the pulse to the weight of the point mass. To associate tolerance levels with the DRI, the DRI was calculated for existing ejection seat designs. The computed DRI values were plotted against the percentage of ejections in which spinal injury occurred; the curve thus obtained represents an approximation of injury probability as a function of DRI.

Both the simple occupant model on which the DRI is based and the DRI itself are very limited in application: the simple model could only be used for cases in which the loading is purely vertical, that is $+G_z$ such as in ejection seats. It is obviously not applicable to model a restrained occupant under forward loads; in this case the main effect is the combined stiffness of the restraint system and the occupant's pelvis/chest. Even for $+G_z$ acceleration the model is difficult to use since potentially significant effects, such as the effect of seat pan stiffness, are neglected.

The DRI is based on a model which does not adhere closely to the actual dynamics of an ejection. The seat pan stiffness is not considered, nor is the distribution of body mass along the spine or the weight of the occupant. Thus, the DRI can be expected to produce useful data only in crashes which are pretty much like a seat ejection — that is purely $+G_z$ acceleration, seat pan stiffness similar to the stiffness of a fighter pilot's seat and the occupant strapped tightly in.

The Army Crash Survival Design Guide says of the DRI:

> "Although the Dynamic Response Index (DRI) ... is the only model correlated extensively for ejection seat spinal injury prediction, it has serious shortcomings for use in accident analysis. It assumes the occupant to be well restrained and erect, so that the loading is primarily compressive, with insignificant bending. Although such conditions may be assumed for ejection seats, they are less probable for helicopter crashes, in which an occupant may be

ADDED FEATURES

OLD-PROMETHEUS
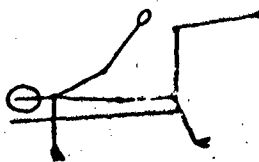
NEW-PROMETHEUS III

● FEATURES
  ● SUBMARINING
    ● PELVIS ROTATION
    ● BUCKLE POSITION
  ● SPINAL CHANGES
    ● 9 SEGMENT ARTICULATION
    ● COMPRESSION/ SHEAR LOADS
    ● COMPRESSIBLE LUMBAR/ NECK
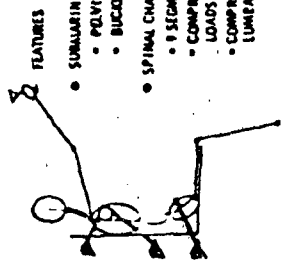
FEATURES

● 7 SEGMENT ARTICULATION
● RIGID HINGE LINES
● BELTS PINNED TO JOINTS
● LIMITED BELT ANCHORS

● IMPROVED RESTRAINT/ SEAT MODELING
  ● OPTIONAL ANCHORS
  ● ADDED STRANDS
  ● HARNESS/ BELT SLIP
  ● FRICTION
  ● VISCOSITY
  ● CUSHIONING/ STRETCH

● IMPROVED INPUT DEFINITION
● IMPROVED GRAPHIC/ TABULAR OUTPUT
● ADDED OUTPUT FORCE (TORQUE/ VELOCITY/ ACCELERATION
● INITIAL POSITIONING AUTOMATED

REFINEMENTS ACCOMPLISHED

BODY DIMENSIONS

MASS DISTRIBUTION

NECK/ WAIST STIFFNESS

MUSCLE TENSION

JOINT FRICTION

PELVIS - DESIGN INTERACTIONS
  ANGLE
  LENGTH
  CENTER OF MASS
  STIFFNESS
  FRICTION

BACK - STIFFNESS
  ELASTNESS
  COMPRESSION

BELTS - ANCHOR POINTS/ ANGLES
  LOCATION/ POSITION ON BODY
  MASS PROPERTIES
  DAMPING
  TENSION
  STRETCH
  SLACK
  LENGTH
  FRICTION

SEAT PAN - ANGLE
  FRICTION
  CUSHIONING
  VISCOSITY

SEAT BACK - ANGLE
  CUSHIONING
  VISCOSITY

PARAMETRIC SENSITIVITY ANALYSES FOR REFINEMENT INCLUDED

● DIMENSIONS
  ● SHOULDER
  ● PELVIS

● DUMMY FLEXING STIFFNESS AND COMPRESSIBILITY
  ● NECK   ● PELVIS
  ● BACK   ● STOMACH

● FRICTION
  ● WEBBING
  ● SEAT PAN
  ● FLOOR
  ● SHOULDER
  ● PELVIS

● WEBBING STRETCH

● VISCOSITY
  ● DUMMY BACK
  ● BODY CONTACT POINTS
  ● SLABBING
  ● CUSHIONS

RESULTING PROMETHEUS III FEATURES APPROXIMATED CAMI CONDITIONS FOR DATA OBTAINED, i.e.,

● DUMMY DIMENSIONS AND MASS DISTRIBUTION
● PELVIS COMPRESSION
● CUSHION FRICTION
● WEBBING STRETCH

CALIBRATION STATUS-BASED ON CAMI TEST DATA

— WITHIN 30% ON
  ● C, CHEST, HEAD
  ● HARNESS LOADS
  ● BELT LOADS

— WITHIN ABOUT 10° ON PELVIS ROTATION

— REASONABLE TIME HISTORY FOR ACCELERATIONS, LOADS

— TIME HISTORY TRENDS REASONABLE, LOADS LOW FOR C, CHEST, HEAD

Figure D-3.9 – PROMETHEUS III Computer Simulators Capabilities and Calibration Refinements
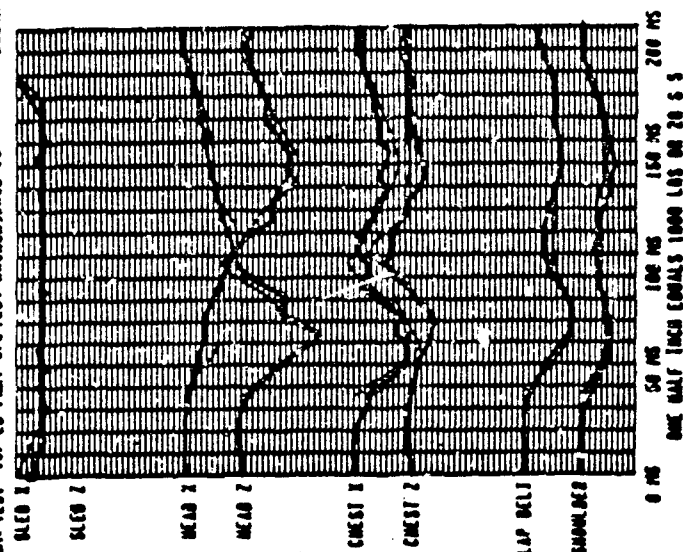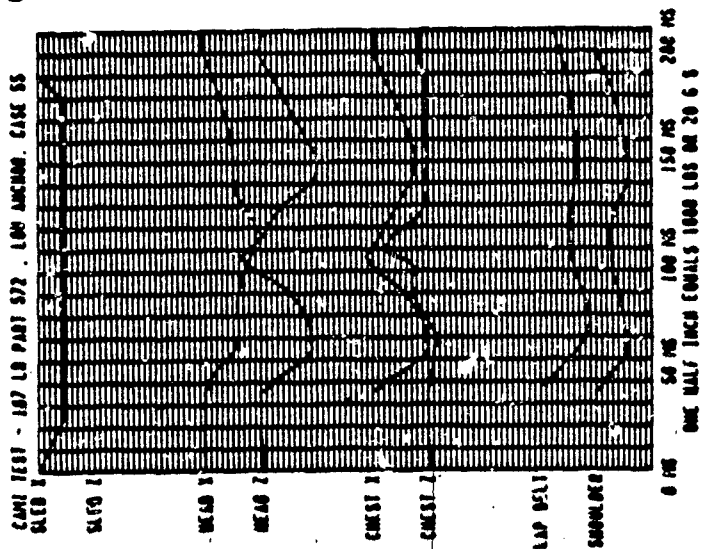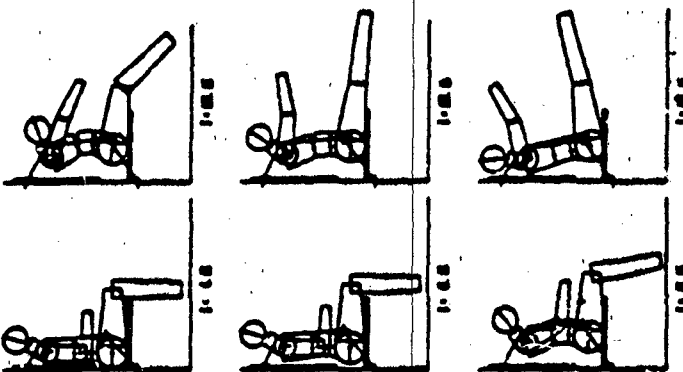
Figure D-3.10 – PROMETHEUS III Simulations

leaning to either side for better visibility at the time of impact. Further, the DRI was correlated for ejection pulses of much longer duration than typical crash pulses."

"A more detailed model of the spinal column would yield more realistic results, but injury criteria for the more complex responses have yet to be developed. Consequently, the DRI is not recommended as the criterion for use in designing crashworthy seats."

Review of Two-Dimensional and Three-Dimensional Occupant Simulation Computer Programs — The following discussion reviews and compares the two-dimensional program PROMETHEUS III (ref. D-8) and the three-dimensional seat-occupant model — light aircraft (SOM-LA) (ref. D-7).

PROMETHEUS III was developed at Boeing in a series of applications for varied purposes, starting from the Dynamic Science program, SIMULA. The focus of the most recent, PROMETHEUS III, has been on accurate modeling of the occupant and restraint system. PROMETHEUS III has since been used extensively to develc data for assisting in engineering design decisions.

SOM-LA development was sponsored by the Federal Aviation Agency through a series of contracts with various companies and universities. The emphasis in SOM-LA development has been on the detailed seat model. A new version of SOM-LA, termed MSOM-LA was completed under number DTFA03-80-C-00098. The occupant model has been upgraded in MSOM-LA.

Development of Basis of Evaluation — Boeing is one of very few places that an occupant simulation computer program (PROMETHEUS III) has been developed and demonstrated sufficiently to be used as a trade-off tool in the engineering design process. This experience is drawn upon to establish criteria for continued evaluation of occupant-simulation computer programs.

The design questions for which PROMETHEUS III simulations were employed to provide engineering data were quite varied; the common denominator was that all questions related to relative occupant safety. Of course, and due in part to the limitations of existing human tolerance data, it is rarely possible to predict with certainty whether injury would have occurred in a given crash on the basis of a computer simulation; similar questions may also be unanswered in dummy tests. However, in most cases, computer simulation is the only practical method for obtaining trade-off data for specific questions, and on a timely basis.

To be usable for this sort of design question, an occupant-simulation computer program requires two major attributes.

First it must be able to model a very general structure (not just a seat), and be able to model contact between the occupant and any part of the structure. (For example, impact of an occupant with the seat ahead).

The second feature is that the program must provide data which may be used for estimation of comparative injury potential. This means that:

1. The program must have been calibrated by predicting to test data (preferably from live human tests or from dummies demonstrating at least partial correlation with human data).

2. Time-histories of forces acting on individual body segments of the occupant model should be printed and/or charted.

3. Time-histories of torques acting in joints of the occupant (e.g., the elbow) should also be printed and/or charted.

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4. Time varying internal loads acting on flexible body segments (such as the lumbar spine) should be printed and/or charted.

Of course, the standard software features relating to ease of program use are also desirable — that is, ease of input, automatic data checking, legibility of output, and availability of graphic aids.

Comparative Evaluation of PROMETHEUS III and SOM-LA — Figures D-3.11, D-3.12, and D-3.13 constitute checklists of features needed for engineering design usage of occupant-simulation computer programs. Checklist items were obtained pragmatically from experience in using PROMETHEUS III to develop design trade-off data. The amount of use of PROMETHEUS III justified incorporation of most checklist items into PROMETHEUS III; consequently the lists serve mainly to indicate desirable improvements in SOM-LA. An improved version of SOM-LA is named MSOM-LA. The main improvement in the new model is an improved seat model which is capable of modeling energy absorption. The occupant model has also been improved by the incorporation of a flexible segment representing the lumbar spine.

The major deficiency in PROMETHEUS III is that it has only been possible to perform limited, exploratory calibration against live human test data and for similar reasons limited exploration of seat model dynamics. Added calibration of this type is desirable. A benefit is that mechanisms within the two-dimensional PROMETHEUS III model are easier to comprehend than those within a three-dimensional model, giving an added plus for initial use of a two-dimensional model in calibration efforts. Other than development which may be required to achieve such calibration, further model evolution must consider limitations intrinsic to the two-dimensional nature of the model and distinguish the conditions for using a 2-D or a 3-D model. Of course, current uncertainties in the level of human tolerance to transient loads are a constraint that must be observed for either 2-D or 3-D models.

SOM-LA could benefit from both human data calibration and model improvement (from the standpoint of usefulness for engineering design). There are two major modeling deficiencies — the restraint system model and the difficulty of modeling nonstandard seats and structure. Both represent difficult modeling problems in a three-dimensional environment, and the methods developed to simulate these features in the two-dimensional PROMETHEUS III computer program do not readily generalize to three dimensions.

SOM-LA has a very primitive restraint system model. The restraining belts are pinned to the body, so realistic modeling of a restrained occupant is impossible. SOM-LA also has limited flexibility in the type of restraint system which may be modeled. Nonstandard configurations, such as restraint system with crotch or thigh straps could not be simulated. In addition, harness friction is implemented incorrectly (friction is crudely and incorrectly simulated by reducing the tension in the strap segment running from the lap belt to the shoulder by 12%). Another serious defect is that chest compressibility (which effects shoulder harness loads) is not modeled.

Accordingly, this simple restraint system model is inadequate for engineering design use for evaluating restraint system performance. It introduces uncertainty into the accuracy of predicted body loads and accelerations, since the dynamic performance of the restraint system is one of the primary sources and conduits of transmission of crash loads to the occupant.

The second major SOM-LA deficiency is the limited seat structural configurations which may be simulated. It is possible that more generality is available in MSOM-LA. In addition, it is desirable that MSOM-LA be capable of simulating contact between the occupant and an arbitrary structure (e.g., the back of the seat ahead). This finite element "contact problem" is difficult and is the subject of current research (e.g., reference D-8).

```
=======================================================================

        FEATURE                  PROMETHEUS III    SOM-LA        MSOM-LA
                                                                 (Note 1)
-----------------------------------------------------------------------

I    Occupant
        Segment masses, length,      I,D            I,D           I,D
         inertias, c.g.'s.
        Mechanical properties        I,D            D             D
         of joints

II   Restraint System
        Mechanical properties of     I,D            I             I
         lap belt
        Mechanical properties        I,D            I             I
         of harness

III  Seat
        Geometry                     I,D            I             I
        Construction                 I,D            D             I
        Mechanical Properties        I,D            I             I

IV   Crash Pulse                     I,D            I             I

VI   Interactive (Conversational)    X              -             -
        input feature


-----------------------------------------------------------------------

        I = Input, D = Default (i.e., supplied by program)

Note 1:   It is assumed that the MSOM-LA input is essentially the same
          as the SOM-LA input.

=======================================================================
```

Figure D-3.11 – Comparison of Program Input Features

FEATURE	PROMETHEUS III	SOM-LA	MSOM-LA (Note 1)
I Occupant			
Segment cartesion position, velocity, acceleration	X	X	X
Segment angular position, velocity, acceleration	X	-	-
Forces on segments	X	-	-
Joint Torques	X	-	-
Spinal Loads	X	-	-
II Restraint System			
Lap Belt Load	X	X	X
Harness Load	X	X	X
Belt Slip	X	-	-
III Seat			
Cushion Forces	X	X	X
Reactions	X	X	X
Nodal Forces	X	-	-
Element Forces	X	-	-
IV Crash Pulse	X	X	X
V Printer Plots			
Acceleration Traces (vs time)	X	X	X
Snapshots of Victim/Seat	X	-	-
Locus of Segment c.g.'s as Functions of Time	-	X	X

Note 1:   It is assumed that the output features of SOM-LA and MSOM-LA are essentially the same.

Figure D-3.12 – Comparison of Program Output Features

```
===================================================================

        FEATURE              PROMETHEUS III    SOM-LA    MSOM-LA

-------------------------------------------------------------------

I   Occupant
      Spinal Articulation     5 links          4 links   5 links
      Flexible Lumbar Link     X                 -         X
      Flexible Cervical Link   X                 X         X
      Automatic Initial Position X              X         X
        Generation
      Compressible Chest, pelvis, X             -         -

II  Restraint System
      Realistic friction       X                 -         -
      Free to slide on victim  X                 -         -
      Webbing Stretch          X                 X         X

III Seat
      Finite Element Model     X                 X         X
      Bar Elements             X                 X         X
      Beam Elements            X                 X         X
      Plate Elements           -                 X         X
      No. of elements in typical 6*             60        60
        seat model
      Cushion                  X                 X         X
      Energy Absorption        X                 X**       X**
      Aircraft Interior Modeled X                -         -

IV  Crash Pulse
      Translation Components   X                 X         X
      Rotational Components    -                 X         X

V   Calibration against
       experiment
      Anthropomorphic Dummy    X                ***       ***
      Live Human              ***                -         -
```

X Capability Available

---

*   Growth Available

**   According to the SOM-LA developer, Cr. David Laananen, this feature
      does not work in SOM-LA but does in MSOM-LA.

*** Preliminary calibration accomplished.

```
===================================================================
```

Figure D-3.13 – Comparison of Basic Modeling Features

In addition to these research improvements, several straightforward and rather easy software improvements would enhance usability of the code:

1. Calculate and display time-histories of loads acting on the occupant (e.g., spinal loads, segment forces, joint torques).

2. Improve the algorithm for computation of joint torque.

3. Add printer plot "snapshots" of seat and occupant for appraising occupant location at selected times (two views) for realism and possible comparison with slow motion movies.

Incorporation of SOM-LA into Large Crash Dynamics Code

It may become necessary to acquire or predict dynamic interactions of occupant and floor. Simple predictions may be possible with SOM-LA. Action has been started within the government with the goal to marry the 3-D SOM-LA with a large finite-element computer program (e.g., the 3-D DYCAST) in order to model an aircraft crash in a single simulation that more properly couples the dynamics of the occupants and the aircraft structure.

To accomplish this marriage, it is suggested that the occupant/restraint model be extracted from the SOM-LA occupant/restraint/seat model and packaged as a "super-element." The occupant super-element would then be inserted into the large finite-element programs as a module, although, as noted previously, improvements in the SOM-LA restraint system model are needed to model occupant dynamics accurately. The existing SOM-LA occupant/restraint system model would probably be adequate for the purposes of calculating the gross dynamics of the seat.

The finite-element code would be utilized to model the seat — that is, the SOM-LA seat model would not be used. (This presumes the development of a general contact model to simulate forces acting between the seat and occupant). The contact model would be used to simulate seat cushions. This concept has three advantages:

1. Simulation of multiple occupants becomes possible (e.g., a triple seat).

2. Synchronization of the numerical integration schemes (i.e., the procedures for solving the equations of motion as function of time) in SOM-LA and the finite-element program is not required. The integration scheme of the finite-element program is utilized for both occupant(s) and structure.

3. The capability of the finite-element computer can be employed to model very general seat designs.

It would be possible to use the large finite-element program to model the occupant. The advantage of the super-element is that occupant modeling requires some features that are not generally needed in general finite-element modeling of structures, such as limits on angular motion of limbs at joints. Moreover, occupant modeling is rather specialized, and the correct mechanical parameters describing the occupant are not widely known (in same cases supportive data are not known at all and parameters must be inferred by parametric sensitivity testing). Thus, it would be difficult for a nonspecialist to construct an accurate model.

Additional effort would be required to make the occupant super-element work; provision for transmitting input data to the super-element and obtaining printouts of detailed occupant time-histories is required. In addition, the graphics output from the finite-element program (if graphics post processing is available) must be adjusted to draw the occupant(s) in addition to the structure.

The same procedure could be used to lift the two-dimensional occupant model from PROMETHEUS III if a two-dimensional crash simulation were employed. However, there is little benefit to expect from, for example, using such a model in an overturning or cartwheeling light aircraft where violent interactions of all three dimensions of motion would be occurring.

SCALE MODEL TESTING

This third approach to evaluation is constrained by the dynamic operation of all system elements in impact loading. While used in other areas of testing (aerodynamic, bridge design, buildings, etc.) crashworthiness testing using scale models is more difficult, and credibility becomes more suspect when plastic deformation and rupture may occur in the real environment. Such parameters are very difficult to represent in a scale model. Appropriately approximating the material properties in scale models is very difficult.

TESTING

There will remain vast differences in opinion regarding the degree and type of testing needed to demonstrate suitability of a given design. Authors of the new Guide take the position that testing, including "instrumented full-scale crash tests should be conducted to verify analysis performed and to substantiate the capability of the aircraft system to prevent occupant fatalities and minimize the frequency and severity of occupant injuries during crashes of ... criterion level severity." Instrumented drop tests for landing gear should be conducted to verify analytical predictions and performance to G criteria, including, 20 ft/min sink rate with 10° nose down and 10° roll. A drop test to a sink speed test of 42 ft/sec with level attitude should also be conducted. (Helicoptor is implied for drop tests by reference to rotor lift). Static tests for restraint systems are recommended to design loads, with "sufficient dynamic tests" to confirm that analyses are supported by static test. Static tests of components tied to structure by their normal attachment provisions should be required to demonstrate compatability. Proof loading instead of ultimate crash design loads is an acceptable minimum condition.

Design checklists are provided to more easily record and check performance to the above conditions. Fuel cell considerations are added. Fuel cell items are to keep fuel away from impact area and from occupiable areas, with containment emphasized (e.g., avoid projections that might puncture; use frangible and self-sealing couplings where separation might occur).

COMMENT: Army full-scale testing of small, relatively inexpensive vehicles uses drop towers or swings, and testing is obviously dramatically different in achievability and cost for their helicoptor and light fixed-wing aircraft. The contrasting situation is the very large and expensive vehicles that can not be readily positioned on a drop tower or a pendulum swing, such as the large aircraft in Air Force inventory and large commercial aircraft where full-scale impact testing is not done. Certainly, there are many order of magnitudes of difference in complexity, test systems, data interpretation for any serious attempt to do testing with a large, flexible-body aircraft system with extensive structure and complicated structural dynamics.

4.0 HUMAN IMPACT TOLERANCE AND PROTECTION

IMPACT TOLERANCE CONSIDERATIONS

CRASH ENVIRONMENT

The Army aircraft impact loading scenario varies. Severe impacts more typically include a sequence of events, including: (1) landing gear stroke and wheel failure, (2) fuselage, with both ground and fuselage deformation, and (3) energy absorbing stroke of the seat. For Army aircraft, high longitudinal and lateral loads may be applied to the seat after gear and fuselage deformation — some military aircraft use a "well" or depression in the floor to provide stroke distance, and stroke control then becomes important. Additionally, allowing any more longitudinal or lateral deformation "than necessary could increase the risk of head or chest impact on surrounding structure." Stroke limiting and load limiting trade-offs may become necessary.

Crash load trade-offs for the Army's light aircraft as described in the Guide, are based on a series of worst case situations for each of several components with little or no accumulative "credit" for beneficial features for each that contribute to an overall improvement. Thus, design criteria are specified for components, as well as for the entire system. One example given as a justification is gear stroke and failure that may occur in a way contributing to lateral loading, such as from a single gear failure, or from hitting the ground with a high roll angle. In helicopters, continued rollover appears common, even without added impulse from the main rotor blades after gear failure. Accordingly, the Guide authors have concluded that multiple directional, complex, and violent crash kinematics of Army aircraft (including flip over or upside down impact) demand strength requirements in all directions, including upward and aftward. Lower impact load criteria are imposed for those Army aircraft that are less likely to encounter some of the conditions. Crash environment studies for Army vehicles also distinguish between impact loads for light fixed-wing aircraft and helicopters. Fixed-wing stall/spin accidents can produce high lateral loadings with resultants in the longitudinal/lateral (or yaw) plane. Helicopters show a high incidence of side impacts or rollover after accidents.

IMPACT INJURIES

In Army systems, head injuries were the leading cause of major and fatal injuries, accounting for 31% of all fatal injuries. Leg and chest injuries tended to be next, varying in rank from one airplane to the next.

Breakdown of injuries according to aircraft type demonstrated that serious vertebral injuries were lower for light fixed-wing aircraft and cargo helicopters than the others. The rationale presented is that the stall/spin characteristic of the fixed-wing aircraft and the larger crush distance beneath the floor of the cargo helicopter reduced vertical loads.

HUMAN TOLERANCE TO IMPACT

Discussions of human tolerance point out that in spite of the multitude of experiments, few criteria useful in system design have been developed and validated.

Tolerance data presented are relatively standard in the literature, most particularly from a summary reported by Eiband (figure D-4.1, from the U.S. Army's Aircraft Crash Survival Design Guide, also used in ref. D-3). These authors reference conditions where injuries have occurred in some particular cases as a basis for avoidance. Reported are bases for Head Injury Criteria (HIC) (recommended), and DRI for spinal injury criteria (not recommended, see "Evaluation Techniques",
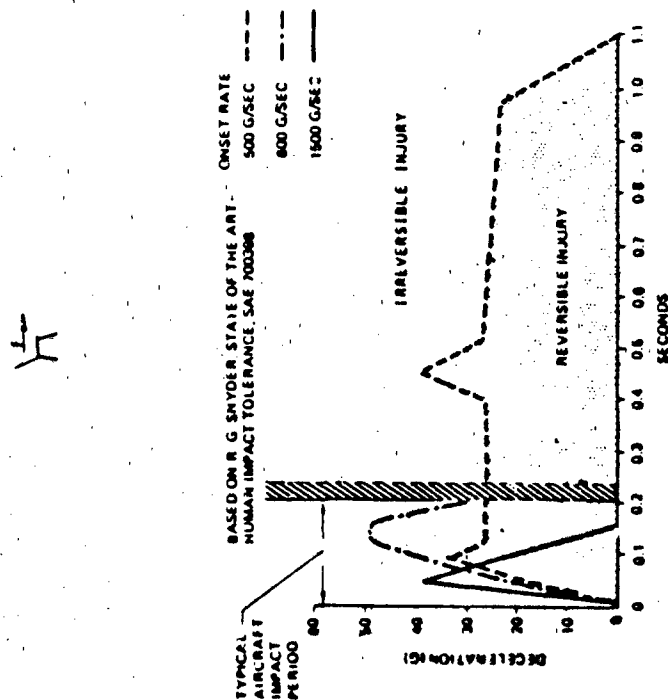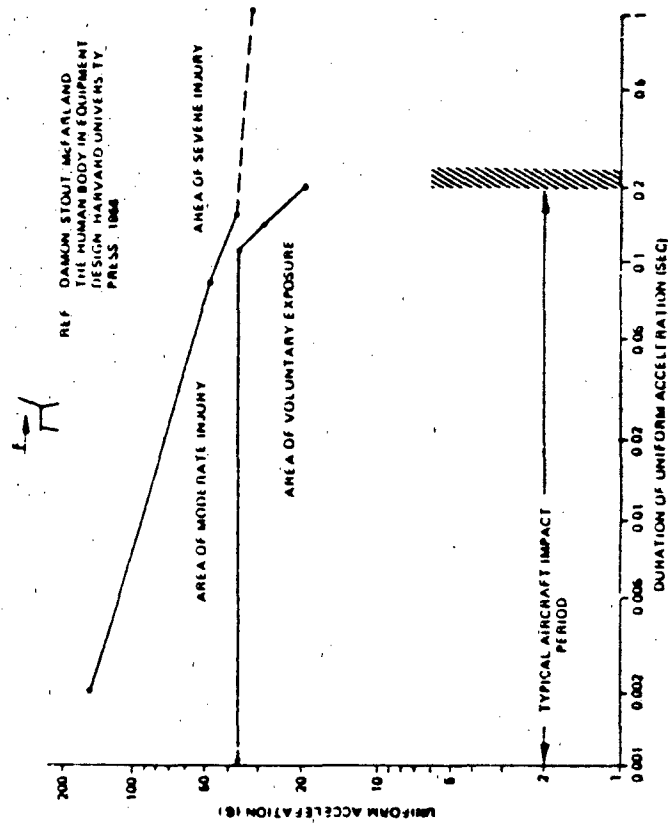
Figure D-4.1 – Fore and Aft Whole-Body "Tolerance Limits"

page to come). In the Guide, leg injury criteria are established at 2000 lb for time less than 20 msec. "Although some research has been conducted on the tolerance of other body parts, such as the neck, thorax and abdomen, well defined valid criteria have not been established." Variations in leg injury data presented in the Guide illustrate the point. Additionally, numerous related literature reviews have been conducted. Results from an Aerospace Industry Association Study by the Transport Airworthy Requirements Committee (AIA-TARC Study, ref. D-3) are repeated in Figure D-4.2 for information purposes.

Actually, data regarding human tolerance to impact still leaves many areas for uncertainty and disagreements. One obvious difficulty is that stressing the live human body to tolerance limits is impossible. Tests with volunteers are necessarily at subcritical levels. Accordingly, animal research has provided much of the data that is used. Additionally, human cadavers have been used as test specimens. However, age, sex and state of health for live people (and for cadavers) can influence tolerance. Additionally, mathematical models and anthropometric dummies are being used to develop better understanding of the kinematics and forces involved and to develop an improved mechanism for injury prediction.

Overall probability of survival depends to a large extent on manner of restraint, particularly to control the upper and lower torso and protect the head and chest. Strongest restraint load points for such control are the pelvic girdle, the shoulder structure, and the rib cage. Restraint effectiveness is related to contact area and force distribution, the body location for application, and the degree to which residual movement is controlled. However, protecting the arms and legs from contacting the interior during flailing is concluded by authors of the Guide to be extremely difficult; in most cases, the cocoon that would be required to produce such containment is quite impractical. Another problem is caused by loose restraint, which contributes to magnified accelerative forces. The abrupt halt in forward occupant motion with the taking up of the slack in restraint then magnifies restraint loads on the body and on the hardware — a condition called dynamic overshoot.

The authors of the new Guide indicate that their main areas of concern for configurations featuring only a lap belt are the potential for head injury and the potential for submarining. They urge use of a shoulder harness in addition to the belt as a favored solution, although it is recognized that connecting the harness to the belt buckle will pull it up and increase potential for submarining — which could load up the abdominal wall as well as flexing the spinal column. To counter this potential, a lap-belt tiedown is recommended by the authors of the Guide, and is actually used by all services.

COMMENT: In a survey conducted for the TARC 216-10 study, leading experts in the field were specifically questioned about this, with none reporting to have observed submarining when only the lap belt (without shoulder harness) was used. Trade-offs of belt-harness characteristics will be presented in a later paragraph.

WHOLE-BODY ACCELERATION TOLERANCE

The Guide authors emphasize a fact that is seldom discussed. Whole-body chest-to-back tolerance has been demonstrated to be as much as 45 G for pulse durations less than 0.044 sec. This decreases to 25 G for 0.2 sec. Some debilitation and injury may occur at these levels. In other words, survivability is not a nice simple constant that is readily engineered, and man is not necessarily a 45 G system.

Tolerance estimates for aftward loading (eyeballs in) are not accurately established. Forces of 83 G for 0.04 sec has been experienced in a backward facing seat, followed by debilitation, shock and on-the-scene medical treatment. Accordingly, the authors estimate tolerance to be between this 83 G and the 45 G, 0.1 sec condition accepted for the forward facing case.

HEAD & NECK	SPINE	EXTREMITIES	SOFT TISSUE ORGANS	CHEST
Beckman & Palmer 1969	Ewing 1971	King 1973	Kourauklis 1972	Kourauklis 1972
Bendnen 1970	Ewing 1973	Kroell et al 1976	Ommaya 1968	Kroell 1971
Brinn & Staffeld 1970	Kourauklis 1972	McElhaney et al 1967	Stalnaker 1973	Kroell et al 1974
Chow 1974	Patrick et al 1970	Melvin 1969	Mertz & Kroell 1970	Mertz et al 1971
Ewing 1963	Prasad et al 1974	Melvin 1975		Nahum et al 1970
Ewing et al 1969		Patrick et al 1966		Patrick et al 1966
Ewing et al 1976		Patrick 1970		Patrick et al 1970
Foust 1973				Schmidt et al 1975
Husk 1966				Stalnaker 1973
Hodgson 1970				Mertz & Kroell 1970
Kickiberg 1966				
Kourauklis 1972				
Lissner 1960				
Martinez 1965				
Melvin 1969				
Muzzy & Lustick 1976				
Nahum et al 1968				
Nahum & Smith 1976				
Patrick et al 1966				
Patrick 1966				
Patrick et al 1970				
Robbins et al 1974				
Snyder et al 1975				
Stalnaker 1973				
Swearingen 1962				
Swearingen 1965				
Swearingen 1966a				
Swearingen 1966b				
Walker et al 1969				

REPORTED BODY PART TOLERANCES
(Summary From Literature Cross Section)

Clavical	1200 pounds		Knee	1500–2650 pounds
Chest	1200–1400 pounds		Head	950–1650 pounds
Spine – Axial Loads			Face	240–1600 pounds
Cervical (C3)	– 900 pounds			
Disk	1100–2800 pounds			
Lumbar	2860–3300 pounds		Abdomen	750–3060 pounds
Femur	1400–1700 pounds			(Based on belt loading and survival with internal load)

Figure C-4.2 – Literature Sources for Body Tolerance Data

Vertical (eyeballs down) loading threatens lumbar compression fracture, again with a variable range for injury potential; potential for visceral injury is also greater, since vertical loads place a greater strain on the suspension system. Eyeballs up loads are on the order of 15 G for 0.1 sec.

Lateral accelerations are less well explored. Volunteers, with only lap belts, withstood 9 $\overline{G}$ for 0.1 sec. With belt and shoulder harness they withstood 11.5 G for 0.1 sec. Other, less well protected lateral impact cases have apparently suffered serious injury.

From the information presented by Guide authors, rate of onset for the force also has an influence, although one that is not well understood. Rates as high as 28,000 G/sec have been survived under very special circumstances which provided an exceptional distribution of body loads. In general, lower rates of onset are preferable.

According to Volume II of the Guide several scales have been proposed for tolerance of various body members:

1. Head-Windshield Impact: Gadd Index
J-Tolerance
Effective Displacement Index
Wayne State Tolerance Curve

2. Neck Impact: No index. Two studies of tolerance to rotation

3. Chest Impact Abbreviated Injury Scale

4. Abdominal Impact Little Data. Marked disagreements between investigators.

5. Spinal Injury Potential Models estimating loads available

DRI (spinal deformation, force) (simple model of complex system)

Wayne State University two-dimensional model

Air Force Head Spine Model

6. Leg Injury Femur Injury Criteria Peak load of 1700 pounds

COMMENT: Results from using such scales provide guideline information that can be used for "order-of-merit" purposes. Some unpublished reports suggest that further research and development might be warranted; factors of two or more difference between resulting "criteria" and undamaged survival are not unusual.

OCCUPANT MOTION ENVELOPES/STRIKE ZONES FOR PROTECTIVE CONSIDERATION

Since kinematics of body action can be violent, dynamic responses of the body with different restraints have been evaluated to define the motion envelope (including flailing) of all body parts. Earlier discussion pointed out that containment of limbs was difficult-to-impossible. Lateral displacement of the upper torso may be extensive, even with a shoulder harness. However, clearing the strike zone of structural parts may not be feasible. The alternative is to design so that injury potential is minimized, e.g., by energy absorbing supports and padding material.

"CLEARED/PROTECTED" (Strike Zone)

Body strike zones are defined for a 95th percentile Army aviator during a downward acceleration,

wearing a restraint system consisting of a lap-belt, crotch strap and shoulder harness. A lap-belt-only configuration strike zone is used for older Army aircraft. (fig. D-4.3). Hazards are rated as primary (threat to head and chest), secondary (lower extremity injury or entrapment), and tertiary (upper limbs). For Army purposes, head protection is considered essential, using helmets, padding and energy absorbing structure.

Areas identified for flight crew protective measures include the instrument panel (padding, frangible breakaway or ductility), rubber pedals (avoid crushing entrapment), control column (break 4 in. above the pivot point, none through the instrument panel). For the gunner, identified areas include eyepiece location, inertial harness, a power haulback inertial reel, inflatable restraint to reduce slack, frangible/ breakaway/collapsable features (not to exceed 500 lb of force).

HUMAN BODY DIMENSIONS AND MASS DISTRIBUTION

The Army Guide uses specific criterion dimensions for design of physical or mathematical simulators of the body. Details are reported in the Guide and will not be presented here. Those presented cover male U.S. Army aviators and soldiers for 5th, 50th and 95th percentile and so are not appropriate for women. Also, information on complete dimensional movement (e.g., shoulder joint ranges of motion) is presented, as are inertial properties.

HEAD-IMPACT HAZARDS PROTECTION

Geometry of probable head impact surfaces is distinctly different from the flight deck to cabin areas. Contact hazards in the U.S. Army inventory in 1965 were identified as including the following:

Flight Deck: Window and door frames, consoles, control columns, seat backs, electrical junction boxes and instrument panels.

Cabin Area: Window and door frames, seats and fuselage structure.

Protection can be provided by energy absorbing padding materials, frangible breakaway panels, smooth contoured surfaces or ductile materials in such typical hazard areas.

OTHER IMPACT PROTECTION

Concerns as expressed in the Guide include:

1. Instrument Panel Structure: Consider use of energy absorbing padding, frangible breakaway panels, or ductile panel materials.

2. Rudder Pedal Protection: The Guide maintains that, unless a tiedown strap is used, pelvic rotation will almost invariably occur with feet on rudder pedals and with forward and downward loads, especially if belt is loose. To avoid complications from the various possibilities, the pedal should support both the ball and heel of the foot. Potential for entrapment or crushing of the seat should be considered.

3. Control Columns: Control of fracture point to near the pivot point is urged. Panel mounted controllers are not recommended; fracture consequences are considered too uncertain by the Guide authors.

4. Sighting Systems: Location and frangibility and restraint power haul back inertial reel.
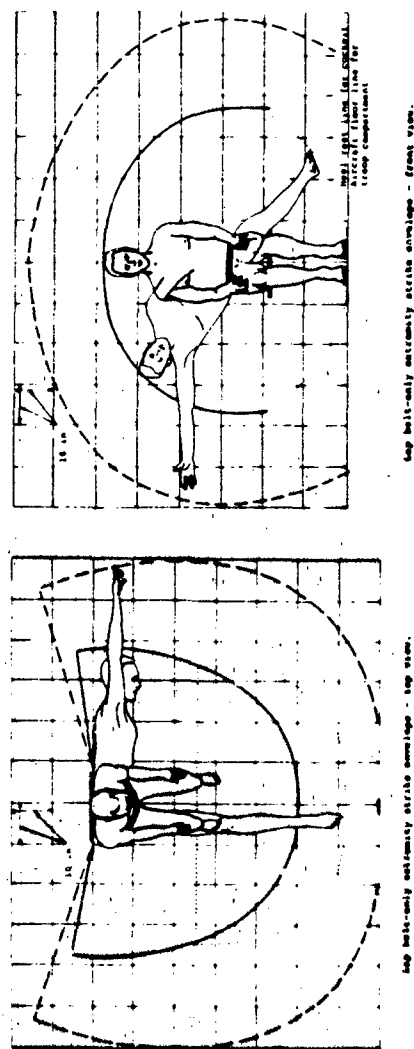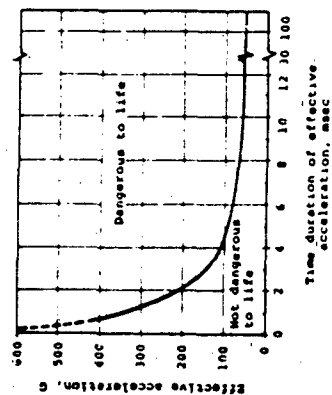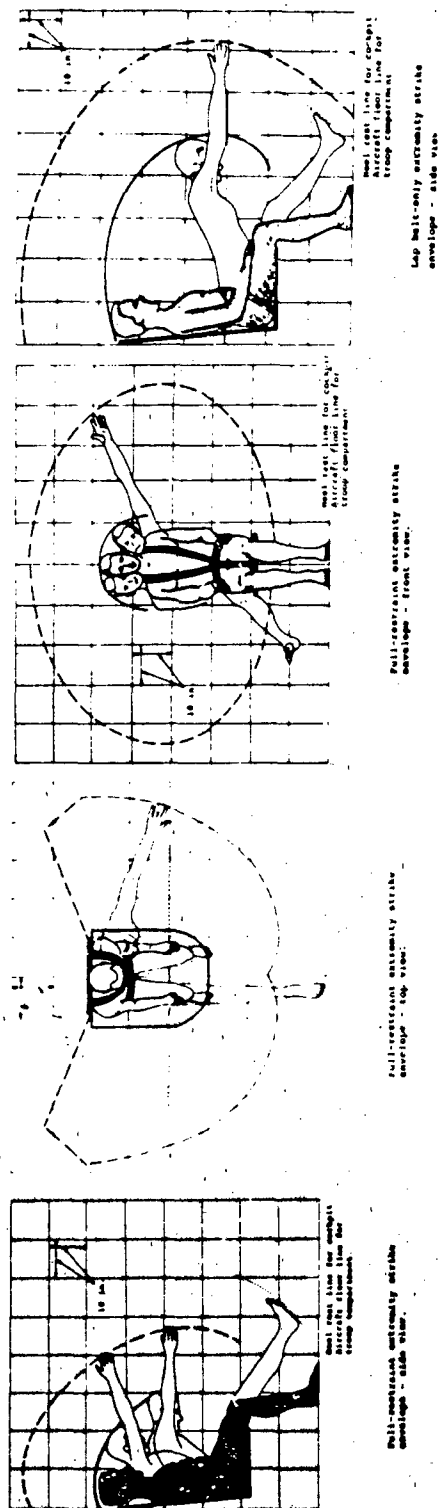
Figure D-4.3 – Strike Zones (From Army CSDG)

For cockpit and cabin interior, energy absorbing padding were recommended in the Guide for use within the strike zone. Desired characteristics included:

1. Adaptability and ease of processing

2. High energy dissipation

3. Effective load distribution

4. Low rebound

5. Temperature insensitivity

6. Low water absorption

7. Resistance to chemicals, oil, ultraviolet radiation, and sunlight

8. Nontoxic fume generation

9. Favorable flammability rating

10. Minimal smoke generation

11. Durability and long life

12. Cost competit. ··

13. Aesthetically acceptable

CRASH TEST DUMMIES

In spite of their limitations, dummies remain one of the primary test tools for dynamic tests. Early dummies developed in 1949 have progressed through several evolutions to a standardized, more sophisticated dummy specified for the Federal Motor Vehical Standards (Part 572) by the National Highway Traffic Safety Administration. Several more recent designs have emerged, all with the objective of improving dummy response and repeatibility of performances. Some comparison of dummy and cadaver response has been accomplished. Comparison tests of dummy designs have been produced, demonstrating among other things that complex dummies increase the number of test variables to a level that may exceed experimenter ability to control the variables or understand the interactions in results.

5.0 AIRCRAFT SEATS, RESTRAINTS, LITTERS AND PADDING

This section of the Guide commences by emphasizing the subsystems that interface with occupants, (including the controls as well as seats, restraints, litters and padding) and also the basic operational differences between crew seats and passenger seats. It distinguishes between passenger seats and litters for transport and crew seats, emphasizing that the crew's functional requirement and operational responsibilities are "of highest priority" while maintaining that comparable "crashworthiness" protection is needed.

BACKGROUND DISCUSSION

Introductory comments in the Guide express the position that a complete systems approach must be employed to include all influencing parameters, including economic restraint, concerned with the design, manufacture and overall performance of the aircraft in meeting mission requirements. However, an accumulative systems capability to protect or absorb energy is disallowed; maximum capability from each component is emphasized.

The intent of this section is to define minimum crash energy absorption "requirements" for seats and restraint systems. Specified strength requirements are based on the crash environments adopted in the Army guide update, as are test requirements.

COMMENT: The seat design requirements stated in the Guide are based on the extreme crash loads postulated to occur in the "95th percentile survivable Army light aircraft crash." No recognition is given to the drastic differences in peak loads from the 95th to the 90th percentile which suggest that the 95th percentile used in the Guide may deviate so far from the normal (and implied) use of such statistics as to be unrealistically and excessively high as a criteria. Other guidelines are also influenced by the assumed load levels. The Guide strongly suggests that seats should be designed with a vertical energy absorbing stroke to mitigate the assumed high vertical loads; little discussion is given to interaction between vertical and other dimensions during the stroke. Better understanding of the influence and means of controlling such interacting parameters is needed.

SEAT INSTALLATIONS

Per military specification, "each seat occupant is to be provided with a survivable environment when the aircraft is subjected to a 95th percentile potentially survivable impact." This will require energy absorption and maintenance of "un-intruded" living space to avoid debilitating injury that might preclude timely egress after crash impact. Candidate methods are many; sufficient absorption by landing gear and structure could leave little requirement for energy absorption in the seat. The converse also holds, requiring a long seat stroke. Restraint design loads transmitted through the seat to the structure are another variable.

Vertical energy absorption is mandatory in Army aircraft seat component specifications because landing gear also might fail; a 12-in. minimum stroke is recommended, but may be precluded by desired positioning of the seat within the aircraft.

COMMENT: The objective correlates with a total airplane objective but continues to leave questions regarding statistically unusual and dramatic differences between 90% versus 95%. It does not provide assurance that these "whole body" loads define seat loads, and leaves in doubt the accumulative effect of such elements as slack or mispositioned harness which may be beyond the control of the designer.

PRIMARY DESIGN CONSIDERATIONS

Primary design considerations for protection include the design of the seats to be retained in position and use of an integral means of crash load attenuation. Additionally, the occupant's strike envelope should be "delethalized", a term interpreted by the present reviewer to mean padded, frangible, and/or ductile or otherwise designed so as to aid in the prevention of serious injury. Structural distortion is discussed in terms of its possible benefits for energy attenuation but also of concern is the extent of and effects of intrusion into the occupant envelope. Trade-off studies are necessary.

RESTRAINT/SEAT/LITTER/PADDING DESIGN CONSIDERATIONS

The U.S. Army's position is that occupant protection and survival should be a primary design consideration for seats; seats should "be retained generally in their original positions within the aircraft throughout any survivable accident." Additionally, "the seat should provide an integral means of crash load attenuation and the occupant's strike envelope should be delethalized."

Seat comfort is considered a pilot's safety-of-flight factor, reducing potential for pilot fatigue in a short time period, rather than a crash safety design factor. Pilot comfort "must not be unduly compromised to achieve crash safety." Back angles over 13° and thigh tangent angles 5 to 20° are recommended in the Guide. (Influence of seat angles will be discussed later).

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Flight crew seats are typically adjustable, to locate the eye position for any precentile body size at the design eye point.

COMMENT: Comfort and safety requirements may be in opposition, as is the case for the seat back angle and for the rigid foam needed for energy absorption versus the soft foam desired for comfort. Alternatively, discomfort may lead to erroneous adjustments and improper use of the protective designs. Accordingly, to some extent, a design may reflect trade-offs related to the unique application.

DESIGN PRINCIPLES FOR SEATS

The Guide authors point out that seats face any direction, and that forward facing is most common, but prefer aftward facing. Aft facing seats provide "maximum contact area and support." For forward facing flight deck seats, the authors also recommend a lap-belt tiedown (crotch) strap for flight crewmen and consider lap-belt-only restraint undesirable; both upper and lower torso restraints are recommended. They consider side-facing seats least desirable but suggest that when side-facing seats are used, an upper torso restraint resisting forward motion is needed. Ductile materials (for energy absorption) featuring at least 10% elongation are recommended for all critical members in the primary load paths of nonload limited seats, and featuring at least 5% elongation for loadlimited seats).

Seats

For Army purposes, Guide authors state single occupant seats are preferred in order to avoid complicated energy absorbing situations that may occur for multiunit seats that are not fully occupied. Guide authors considered it desirable that all seats face in the same direction to protect occupants from loose equipment.

Aftward facing seats were preferred when practical, to "maximally distribute body contact area." Forward facing seats were considered to afford "adequate protection by the use of a restraint system consisting of shoulder straps, a lap-belt and a lap-belt tiedown (crotch) strap." The authors consider lap-belt-only restraints undesirable.

COMMENT: Many systems accept this configuration with an energy absorbing surrounding area.

Forward facing seats with adequate restraints are acceptable as a second choice to aftward facing seats. When single diagonal upper torso restraint is used, it should pass over the outboard shoulder to contain lateral impact or protrusion outside the aircraft.

Previous side facing seats were provided with lap-belt restraint only. This arrangement was considered by Guide authors to be inadequate, and least desirable from the crash safety standpoint; however "when no reasonable alternative to their use exists, adequate restraint must be provided. If a single, diagonal upper torso restraint is used, it should be placed over the forward facing shoulder" (relative to the aircraft).

Shoulder harness provides minimal protection to abrupt acceleration in the side facing configuration. Lateral torso movement should be minimized or prevented.

Litters

The supine position that litters provide is ideal for resisting vertical impacts. The supine position allows maximum possible contact area and force distribution, and forces are transverse to body.

Lateral installation should be provided. It would prevent body from sliding off the litter longitudinally, and prevents the litter from sliding and/or repositioning to become completely detached from supports.

STRUCTURAL CONNECTIONS

Seat Attachment — Cockpit seats are floor or bulkhead mounted. Cabin interior seats may be: (1) suspended from the ceiling with energy absorbers and wall stabilized, (2) suspended from the ceiling with energy absorbers and floor stabilized, (3) wall mounted with energy absorbers, (4) floor mounted with energy absorbers, or (5) ceiling and floor mounted (vertical energy absorbers above and below the seat).

Suspension or mounting of all seats should not interfere with rapid ingress or egress.

Hardware Materials — Material selected for attachment of webbing should be ductile enough to deform locally, particularly at stress concentration points. This ductility is not as critical when energy absorbing provisions are incorporated into the seat. On the other hand, consistent use of ductile materials avoids the possibility of non ductile materials on nonload limited seats. Selection of materials should emphasize:

1.   Best strength-to-weight ratios

2.   Maintaining ductility to prevent brittle failures

3.   Standard elastic analysis/selection methods for most working life conditions

4.   Behavior beyond the yield point analysed for energy absorption purposes.

RESTRAINT SYSTEMS

DESIGN PRINCIPLES FOR PERSONNEL RESTRAINT SYSTEMS

Statistics on U.S. Army aircraft accidents indicate failure of personnel restraint harness as a frequent cause of injuries and fatalities. From Volumes I and III of the Guide, a crashworthy aircraft is to "eliminate unnecessary injuries and fatalities in relatively mild impacts." However, Volume III also states in a different context that the Army goal for seat and restraint systems is to "reduce occupant decelerative loading to within human tolerance limits," that "ideally ... structure should minimize occupant accelerations to survivable levels in a severe crash environment." In other words, Army policies in establishing design principles for personnel restraint systems are to prevent injury to all occupants in crash conditions approaching the upper limits of survivability.

Belt and crotch strap remain the standard for U.S. Army flight crews by recommendation of the authors of the updated guide (crotch straps are to oppose harness loads on the belt). Troop and passenger requirements were different; the most recommended system was an inertial harness over each shoulder connecting to a center-body lap-belt buckle, and secondly, a system with a diagonal shoulder-to-belt anchor strap positioned to restrain the occupant from protruding outside the aircraft during lateral loading (similar to automotive systems).

Inflatable restraint belt and harness were described as a more complex and costly alternative that will reduce restraint slack by automatically pretensioning the system to better control impact response. Another related inflatable alternative is air bags, which are conspicuous in their absence from Guide discussions.

Numerous human body restraint methods have been proposed, investigated and/or used; some are "exceptionally good", others "left much to be desired." Desirable qualities are:

1. Comfortable light weight

2. Easy to put on and remove even in the dark

3. Feature a single-point release easily operated with either hand, and protected from inadvertent release, e.g., being struck

4. Provide freedom of movement to operate the aircraft controls, e.g., through the use of an inertia reel with the shoulder harness

5. Provide sufficient restraint in all directions to prevent injury in a potentially survivable crash

6. Webbing should provide a maximum area, consistent with weight and comfort, for force distribution in the upper torso and pelvic regions and should be of low elongation under load to minimize dynamic overshoot.

GENERAL DESIGN CRITERIA

General design criteria are as follows:

1. Comfort should not be unduly compromised by crash survival systems or improper adjustment by users is a likely outcome. Hardware should not contact bony portions of the torso, and assemblages should be compatible with the desired location on the body. Webbing should not be so wide or stiff as to restrict ventilation (or cause chaffing).

2. Emergency release should be based on a single-point release for the belt-harness combination, operable by either hand with 20 to 30 pounds force and operable regardless of the occupant position (e.g., upside down). However, accidental opening should be prevented. The buckling system should be insensitive to rotation and slight misalignments such as misaligned pins that might shear in series.

3. Lap-belt anchorages involve a series of constraints: a) It is desirable to anchor to the seat or the anchorage must accommodate possible seat motion. b) Both forward and vertical loading must be accommodated. Submarining (i.e., slipping down through the lap belt) should be prevented. However, the lap belt should not restrict freedom of leg motion for pilots. c) When necessary to counteract the up loads of the harness, lap-belt tiedowns (i.e., crotch straps) should intercept the seat pan (14 to 15 in. forward of the seat back). d) Adjustment hardware should carry at least the same design loads as the webbing without slipping, crushing or potentially jamming the webbing. e) Adjustment and release hardware must not be located over skeletal structure (e.g., lap-belt hardware over the iliac crests of the pelvis) and harness hardware should ride as low on the chest as possible. f) All materials should be ductile enough to deform locally (with a recommended minimum elongation value of 10%).

COMMENT: The influence of belt-harness angles are discussed on page 214.

4. Seat structural connections: a) Criteria for bolts should continue as practiced (10 to 25% safety margin and typical 0.25 inch diameter to avoid over-torque), and criteria for rivets and welds should continue as practiced. b) Seat mountings may vary, including combinations of ceiling, bulkhead and floor, all using energy absorbers. Structural joints should permit angular distortions. Similar principles and criteria apply for bulkhead mounted seats. c) Guide authors preferred that restraints be anchored to the seats; the key factor is to permit seat deformation and associated energy absorption to occur (which could be inhibited by anchoring harness to the floor), and without loosening of the belt.

5. Webbing and attachments: Restraint harness also could vary in required load capability, according to whether a load limiter is used. However, authors of the Army Guide suggest a standard, single strength interchangeable harness to avoid risk of a mix up in installation. Minimal webbing elongation is proposed as necessary to avoid dynamic overshoot. It also minimizes potential for secondary impacts; for this reason the Army resists energy absorption applications. Added precautions are necessary where webbing is folded or bent at hardware interfaces, in order to avoid compromising strength requirements, e.g., from concentrated loads or from wear. Energy absorbing webbing is not recommended for use in seating systems.

COMMENT: In computer simulations done in the TARC study, increase in belt strength and corresponding reduction in stretching resulted in a reduction of "submarining tendency", lumbar compression and seat loads but an increase in restraint system loads and thorax loads. The study showed (and personal communication with USAF AMRL confirmed) that a level of belt strength exists beyond which further reduction in stretch avails little benefit.

6. Inertia reels are installed when full freedom of movement for the crewmember is desired. a) Both impact sensitive and rate sensitive reels are used. Rate sensitive reels are preferred by Army for helicopters and light fixed wing aircraft because of the multidirectional possibilities for impact, which may not trigger the impact sensitive system. b) Sometimes, retractors or power haul-back features are also used. When used, powered haul-back mechanisms are used to retract slack (e.g., for seat ejection). However, automated haul-back for crash restraint should be avoided, since the time lapse between triggering and haul-back will result in an added contribution to body loads (the sum of crash and retractor loads). c) Inflatable systems act much faster than automated haul-back and have less take up capability; thus the Army will consider inflatable systems while rejecting automatic haul-back.

TYPES OF RESTRAINT SYSTEMS

Representative restraints used by the U.S. Army are presented in figure D-5.1 (a through e). Configuration (a) is the "minimum acceptable" U.S. Army system. An improved lateral restraint system is illustrated in (b), which adds more shoulder restraint against sideways motion. In (c), a crew chief/gunner restraint system provides for ability to move out of the seat but be instantly restrained when he returns. Troop/passenger systems are illustrated in (d). An automatically inflatable system is illustrated in (e); this one automatically pretensions to force the occupant back into his seat and eliminates potential for looseness and extended dynamic response, e.g., overshoot.

RESTRAINT ANCHORS

Lap-Belt Anchorage

Lap-belt anchors may be on the seat bucket or on aircraft structure. Structural mounting must assure that the restraint remains effective regardless of seat position. Structural attachment will not be practical when the seat includes longitudinal load limiting. Lap-belt anchor location is also considered a comfort factor; locating it too far forward interferes with movement of the legs. This is considered important for pilots but not important to passengers since they are not required to perform operations with their legs.

By Army practice, submarining is considered to be prevented by a lapbelt tie down strap, by locating the belt so its centerline falls 2 to 2.25 in. forward of the seat reference point, and/or by assuring that the angle between the lap belt centerline and the buttock reference line is at least 45° (but not exceeding 55°) for a 50th percentile occupant (fig. D-5.2). The 45 to 55° angle has priority over the 2 to 2.25 in. location dimension. Submarining can also be reduced by ensuring that the lap belt is tight.

COMMENT: Data on which these conclusions are based appear to be twofold. First, from practice, it was long ago presumed that the belt should be anchored low and forward enough to keep it on the pelvis, but aft far enough to keep the occupant from sliding forward off the seat — with 45 to 55° an obvious solution as effecting the most direct compromise between the two (R.F. Chandler, SAFE Panel Discussion on Attendant Restraint Improvement Study, December, 1979, Las Vegas). Another basis appears to have been selected from the data of figure D-5.3, although the referenced sources do not particularly emphasize, for example, that some dummies are predisposed to submarine, or that the only clear source of harness angle data (which these data are from) is based on a bandolier type shoulder harness (with twisting and compression confounded) and a seat with extremely reclined seat back and seat bottom. Shoulder harness criteria were also based on visual

Figure D-5.1 – Types of Restraint Systems

Combined Belt-Harness System Criteria (Implied)

SHOULDER HARNESS ANCHORAGE GEOMETRY

CORRECT

TORSO CARRIES ONLY A PORTION OF SHOULDER STRAP LOAD

SHOULDER STRAP LOAD

RESULTANT

SEAT REFERENCE POINT

MAXIMUM SHOULDER STRAP ANGLE

25°

25.5 TO 26.5 IN.

PARALLEL TO HORIZONTAL VISION LINE

INCORRECT

TORSO CARRIES NEARLY ALL OF SHOULDER STRAP LOAD

SHOULDER STRAP LOAD

RESULTANT

LAP-BELT ANCHORAGE GEOMETRY

SEAT REFERENCE POINT

RECOMMENDED LAP BELT

THIGH TANGENT LINE

LINE PARALLEL TO THE HORIZONTAL VISION LINE

45° - 55°

BUTTOCK REFERENCE POINT

2.5 ± 0.5 IN.

5.75

Figure D-5.2 – NTSB Guideline (USAAMRDL 71-22)

Figure D-5.3 – Belt-Harness Angles From Literature Survey

observation of slow motion film with no physical measurements to support conclusions regarding vertebrae compression.

Shoulder Harness Anchorage

The shoulder harness may be placed either on the seat back structure or on the basic aircraft structure. Strap routing must avoid the possibility of interference or constraints from seat adjustment or energy absorbing stroking. Additionally, the relationship of the harness angle to an aft horizontal tangent to the shoulder should be minimally effected by seat adjustments. The position of the Army Guide is that the aft, horizontal angle of the harness from the shoulder should not exceed 30° up from the perpendicular to the seat back, and the intercept with the seat back should not be lower than 26 in. above the buttock reference line (figure D-5.2). Lateral movement in the seat back guide for the harness should be restricted to 0.5 in. or less.

COMMENT: For lower load levels, a much wider range of angles may be possible; otherwise use of the same seats by men and women would require two harness systems. The result of systematically varying seat belt and harness angles for a traditional "4 anchor" or "4 point" system (with a 9 G crash pulse) is illustrated in figure D-5.4, based on the TARC 216-10 (ref. D-3) application of the highly calibrated PROMETHEUS III model. Selected combinations showed submarining could be controlled over a wider range than had been presumed as indicated by belt slip and pelvis rotation for incipient submarining (2 in. and 27°, respectively, in the model). Additionally, there was no marked influence on estimates of lumbar compression loads within the range of +40° for harness angles and 25°/30° to 70° for belt angle (with broader ranges apparently feasible in some special combinations). (Such data were for a horizontal seat pan and a vertical seat back.)

The TARC study also indicated that seat configuration (i.e., pan angle and back angle) influences restraint system performance. Figure D-5.5 illustrates the variation in performance with a "4-anchor" system as the seat pan and back angles are systematically altered through a range of settings.

The TARC study also showed that changing restraint system design can have a marked influence on restraint system effectiveness. Figure D-5.6 illustrates the change in retention performance with different restraint systems configurations. As illustrated, alternative configurations can provide marked retention improvements with no change in anchorage and no significant penalties.

Lap-Belt Tiedown (Crotch) Strap Anchorage

This strap is to prevent ride-up of the belt when used. It should intercept the seat pan centerline 14 to 15 in. forward of the seat back.

ADJUSTMENT HARDWARE

Adjusters are to carry the full design load of the subassembly of which they are part, without slipping or crushing webbing. Required adjustment force should not exceed 30 lb Adjusters are not to be located over skeletal hard points (iliac crest of pelvis, collar bones).

DELETHALIZATION OF COCKPIT AND CABIN INTERIORS

The main purpose of "delethalization" is to minimize potential for injuries that jeopardize emergency evacuation. The kinematics of body action associated with aircraft crash impacts can be violent, including flailing of body parts. The Army position is that this is severe with only a lap belt as the restraint, but multidirectional flailing is still extensive with a lap-belt/shoulder harness combination.

3/4 ANCHOR RESTRAINT

PELVIC ROTATION

LUMBAR COMPRESSION
(RELATIVE)

BELT SLIP

50% MALE DUMMY

0° SEAT PAN

90° SEAT BACK

4 ANCHOR RESTRAINT

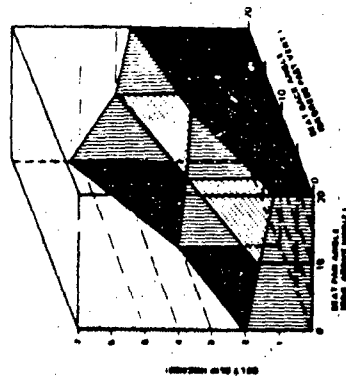15% WEBBING STRETCH @ 2500 #

9G FORWARD LOAD

SIMULATION MATRIX
—BELT ANGLES = 0, 15, 20, 25, 30, 40, 50, 70 DEGREES
—HARN ANGLES = −60, −45, −40, −25, −10, 0, 10, 25,
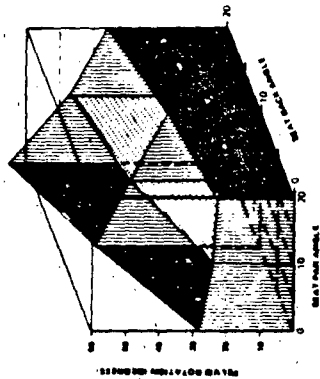   35, 45, 60 DEGREES

Figure D-5.4 - Submarining and Lumber Compression Tendencies With Interacting
Belt-Versus - Harness Angles

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3/4 ANCHOR RESTRAINT

SEAT BACK NORMAL (PERPENDICULAR)
REFERENCE FOR RESTRAINT ANGLES

PELVIS ROTATION

BELT SLIP

LUMBAR COMPRESSION
(RELATIVE)

HORIZONTAL REFERENCE FOR RESTRAINT ANGLES

PELVIS ROTATION

BELT SLIP
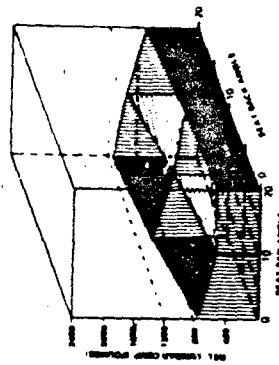
LUMBAR COMPRESSION
(RELATIVE)

Figure D-5.5 - Submarining and Lumber Compression Tendencies With Seat-Versus-Back
Angles

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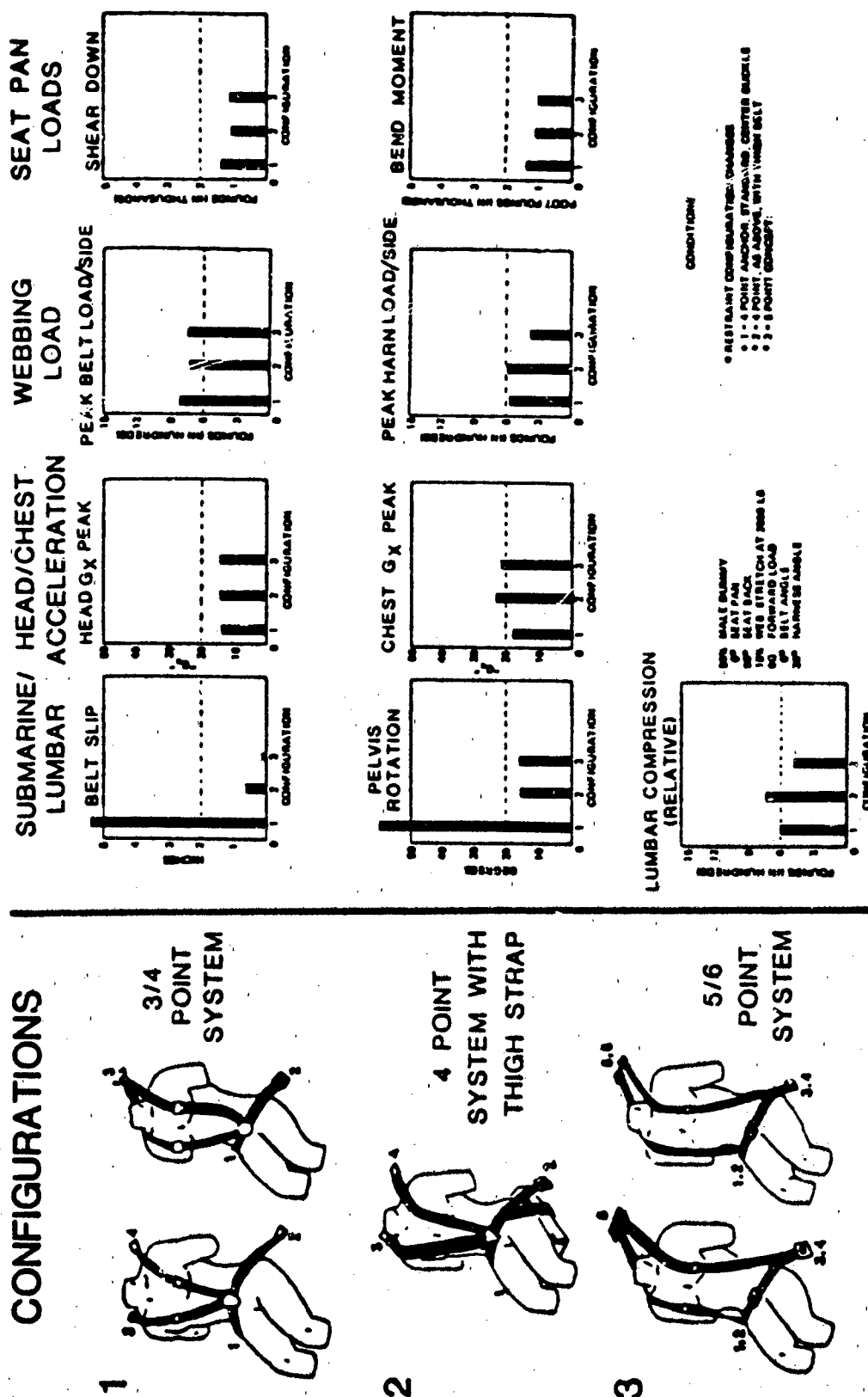
Figure D-5.6 - Submarining and Lumber Compression Tendicies With
Seat-Pan-Versus-Seat Back Angles

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COMMENT: There is little evidence that such dramatic multidimensional and injurious flailing of the limbs occurs in large commercial airplanes. Reports suggest that if it occurs most such action appears to be allied with the primary impact loading in the fore-and-aft direction, since there is little cartwheeling or large lateral acceleration evidenced in large aircraft impact.

The occupants' immediate environment should be designed so that injury potential is minimized if the body parts flail and contact rigid or semirigid structures in the immediate environment. Alternatives are to move the hazardous object (or structure) out of the flail zone, mount it on frangible or energy absorbing supports and/or apply a padding material to distribute contact force over a larger area on the body member.

ENERGY ABSORPTION

Energy absorbing devices are introduced with the statement that the seat structure must possess either the capability of sustaining the maximum inertial forces imposed by the deceleration of the occupant and seat, without collapsing (i.e., deforming or failing), or have sufficient energy absorption capacity to reduce the occupant's velocity to zero before structural failure occurs. The first alternative could involve excessive strength (and weight) requirements to accommodate dynamic overshoot factors of 1.2 to 2.0 (i.e., load factors to twice as large as design loads). The second using controlled collapsing behaviors offers a more practical approach. It does offer the capability to better control force levels relative to human tolerances. Of course, neither approach is totally achievable.

COMMENT: Ultimately, design for any approach will be exceeded; there is no way to assure ultimate survivability. Even the selection of a 95th percentile crash was based on recognition of this fact. Nevertheless, wording frequently overlooks this fact.

CRASH ENERGY ABSORPTION

During crash loads, the occupant's center of gravity acquires a distinct velocity relative to the airframe. Maximum relative velocity may become large. In turn, the seat must sustain the applied loads or possess sufficient energy absorption capability to reduce the occupant's relative velocity before structural failure occurs. The Guide emphasizes the desire to obtain the greatest energy absorbing stroke from the seat (for Army conditions with widely varied impact loads). This receives independent emphasis without regard to energy absorption from other system elements. Increasing occupant stopping distance during a crash can reduce impact loads and thus improve tolerability levels for imposed decelerations. Methods include:

1. Additional crushable airframe structure

2. Energy-absorbing landing gear

3. Seat design with energy absorbing mechanism(s) (e.g., load limiting or controlled seat collapse)

4. A combination of the above

Common misconceptions exist; related comments are:

1. The seat energy-absorbing system does not absorb all the energy associated with the impact velocity.

2 The first comment also explains why slack in the restraint system or seat attachments is undesirable; added stroking to accommodate larger relative velocity will be required to decelerate the occupant.

3. The seat energy absorbing stroke simply lengthens the stopping distance of the occupant by allowing the seat to stroke as other energy absorbing processes are nearing completion.

4. Disregarding dynamic response differences, the same stroke distance is required to decelerate any mass at a given deceleration magnitude. Therefore, lighter people do not require shorter strokes than heavier people (however, a different energy absorption characteristic is required).

COMMENT: Stroking must occur in such a way as to minimize the possibility of entrapment.

ENERGY ABSORBING REQUIREMENTS FOR COCKPIT AND CABIN INTERIORS

Two categories of head impact injury are of primary concern—skull fracture with potential brain damage, and facial tissue and bone structure injury with lesser probability of brain damage. Penetration by protruding objects is also of concern. Trauma from intercranial lesions is mentioned, but without criteria other than to reduce level of acceleration, rate of onset and amount of energy transmitted to the head.

The Army position is that "acceleration experienced during secondary impacts of the occupant with the surrounding structures must be reduced to a tolerable level." Padding material should both reduce the decelerative force and distribute the load for uniform pressure. Candidates for energy absorbing include instrument panels, glareshields, other interior surfaces within the strike zone, and seat cushions.

Empirical System Response — Theoretical and empirical information is presented on dynamic energy absorbing response, on empirical development of crashworthy armored seats, and on load limit devices. Extensive discussion is not warranted for this abstracting summary. (A much simpler calculation method based on handbook data is presented in the appendix D-A to this present report)

ENERGY ABSORBING DEVICES

As summarized for the Guide, a multitude of devices for absorbing energy have been proposed, developed and tested. Desirable features of such devices are:

1. The device should provide a predictable force-versus-deformation trace.

2. The rapid loading rate expected in crashes should not cause unexpected changes in the force-versus-deformation characteristic of the device.

3. The assembly in which the device is used should have the ability to sustain tension and compression. (This might be provided by one or more energy absorbers, or by the basic structure itself, depending on the system design).

4. The device should be as light and small as possible.

5. The Specific Energy Absorption (SEA) should be high.

6. The device should be economical.

7. The device should be capable of being relied upon to perform satisfactorily throughout the life of the aircraft (for Army, a minimum of 10 years or 8000 flight hours) without requiring maintenance.

8. The device should not be affected by vibration, dust, dirt, or other environment effects. It should be protected from corrosion.

9. The device(s) should decelerate the occupant in the most efficient manner possible while maintaining the loading environment within the limits of human tolerance.

Numerous load limiters have been devised. The concepts are illustrated and described in figure D-5.7. Body decelerations tend to normalize near the G level corresponding to the limit load factor of the energy absorbing device. An optimum device cannot be selected for all applications on the basis of available data. Rather, the data of the figure presents concepts and guidelines which can be considered relative to specific applications.

SEAT STRENGTH AND DEFORMATION DESIGN REQUIREMENTS

Design should be based on typical weight of the occupant, not the extreme weight. The restrictions placed on crew seats, including stroke length, control access, and seat armor limit flexibility of design options. The weight of combat gear is not included in Guide recommendations for crew seats. Since the large majority of flight hours are not in combat, it is probable that flight crew members will also be lightly equipped. This minimizes another problem. If the full range of weights were to be accommodated, a weight sensitive energy absorbing system would become mandatory in order to protect the occupants over the full range of weights.

Occupant weights determining the effective design loads for seats recommended design loads are based on 5th through 95th percentile weights for men, i.e., 144 through 222 lb. for crewmem, with 112.6 to 175.2 lb. vertical effective weight (effective weight reduces seat load considerations by the amount of the occupant's legs, which rest on the floor. As the authors point out, the ideal situation would be to permit energy absorbing stroke length for the 95th percentile occupant using deceleration limits based on the 5th percentile (who would load the system less and require more yielding ductility, i.e., a lower yield, for the same load reduction capability). However, as they also point out, compromises must be made since the resulting needed stroke distance will not be available in aircraft. A greater weight variation exists for troops and seats should be designed to accommodate them. The 95th percentile should be considered heavily clothed and the 5th percentile lightly clothed.
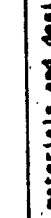
COMMENT: A wide variation in occupant weight cannot be avoided in the commercial environment.

Strength

The Guide authors consider that "an elastic stress analysis, as used in the design of airframe and aircraft components subjected to normal flight loads, is inadequate for the study of all the structure in a crash situation ... the load carrying capacity of components deformed beyond the elastic limit should be considered in determining the ultimate seat strength."

Strength and Deformation

In discussing this subject, Guide authors first point out that some stroking (or displacement) will

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Device description	Energy-absorption process	Operation sketch	Tension or compression	SEA [a] (ft-lb/lb)	Stroke-to-length ratio [b]	Long-term reliability	Ability to sustain rebound loads	Constant load level	Potential application
Strap/wire over die or roller	Metal bending and friction		T and C [c]	1200 [d]	Good - T Poor - C	Good to excellent	Zero to excellent [c]	Excellent	Seat strut or support
Inversion tube	Hoop tension/compression and bending		T and C	1800	Excel - T Poor - C	Excellent	Excellent	Excellent	Seat support
Rolling torus	Cyclic compression and bending		T and C	1500	Good - T Avg - C	Fair to good	Excellent	Good	Seat strut or support
Honeycomb compression	Buckling of membrane "columns"		C	2500-3500	Average	Good	Poor [e]	Fair	Seat strut or support
Basic metal	Elongation of metal tube or plate		T	3000-4500	Poor	Good to excellent	Poor [e]	Fair	Seat support
Basic stranded cable	Elongation of stainless steel		T	3000-4500	Poor	Excellent	Zero	Fair	Seat support or brace
Rod pull-through tube	Hoop tension and friction		T and C	600 [f]	Good - T Poor - C	Good	Poor	Good	Seat support
Tube flaring	Hoop tension, friction, and bending		C	700	Good to excellent	Good	Poor [e]	Fair	Seat strut
Tension pulley	Shear and bending of sheave housing		T	Unknown	Good	Good	Zero	Good	Seat support

Note: Data from Army CSDG.

(a) SEA is very dependent on materials and design. To be directly comparable the devices would need to be designed for the same application. The SEA values for the first three devices listed, those now being used in operational energy-absorbing seats, are reasonably comparable.

(b) In some cases, final length is significant; in other cases, initial length is significant.

(c) Simplest devices operate in tension (T) only; a recently developed troop seat strut is capable of tension (T) or compression (C) (Section 5.3).

(d) Specific energy measured for device that operates in tension or compression.

(e) This device could be rated higher if an integral rebound device were incorporated into the design.

(f) This value is based on the compressed tube device tested. This value could be doubled in a more efficient design.

Figure D-5.7 – Comparison of Load-Line Type Services for 100-to-400 lb loads

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occur for all systems if they are to remain in place during deceleration loads. A minimum displacement must be achieved if the system is to remain in place during a given acceleration pulse. In other words, there is an inherent load deflection curve and travel limit envelope which imposes definite limits on the ability of any system to resist impulse loading. Intentional load limiting is thus the control of this deflection to make best use of the space available in order to absorb energy and to optimize the occupant's capability to survive the loads imposed. Additionally, structural joint deformation should be capable of large angular distortions in all directions without failure, (e.g., bending moment between leg and sitting) including floor distortion and seat pan distortion.

PADDING MATERIALS AND PROPERTIES

Plastic foams are considered by Army Guide authors as the most useful type of materials for energy absorbing padding. Both slab and molded foams are practical, and they are considered by Guide authors to permit selection evaluation based on processability; mechanical, thermal and chemical properties; and cost. Characteristics of "suitable materials" include the following; representative uses are identified in figure D-5.8.

1. Adaptability and ease of processing

2. Nontoxic fume generation

3. Favorable flammability rating

4. Minimal smoke generation

5. Durability and long life

6. Cost competitive

7. Aesthetic

8. High energy dissipation

9. Effective load distribution

10. Low rebound

11. Temperature insensitivity

12. Low water absorption

13. Resistance to chemicals, oil, ultraviolet radiation, and sunlight

Additionally, relevant mechanical properties include:

1. Density		5.	Compressive modulus
2. Tensile strength		6.	Flexural strength
3. Tensile modulus		7.	Flexural modulus
4. Compressive strength			

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1. **Semirigid and flexible urethane foam**

   Aircraft, automobile, and furniture seat cushions, safety padding, arm rests, sun visors, horn buttons, bedding, carpet underlay, packaging delicate products.

2. **Polyvinylchloride foam**

   Crash padding in automobile head liners and sun visors, flooring, shoe soles and heels, automobile door panels, seating upholstery sealants, gaskets, bumperstock.

3. **Polystyrene foam**

   Insulation, packaging.

4. **Expanded rubber**

   Bus and subway seat cushions, truck and ship mattresses, gaskets, hose insulation.

5. **Polyester foam**

   Short-run, custom-type seat cushioning.

6. **Polyolefin foam**

   Packaging, gasketing, water sports equipment, rug underlay, athletic padding, antivibration padding.

Note: Data from Army CEOG.

Figure D-5.8 – Energy Absorbing Plastic Foams and Some Typical Applications

8. Tear strength	12. Rebound
9. Compression set	13. Hardness
10. Compression deflection	14. Impact
11. Elongation	

APPLICATION OF PADDING MATERIAL AND DUCTILE MATERIALS

"In the absence of data for extremity impacts, it is assumed that padding material that is suitable for head impact protection is also suitable for protecting extremities." Strike zone areas with radii of "2 inches or less" should be padded to a "minimum thickness of 0.75 inches".

Ductile energy absorbing materials and breakaway panels should be used where possible. Swearingen (ref. D-9) is cited as demonstrating "that at impact velocities of 30ft/sec against rigid structure padded with materials even 6 in. thick, unconsciousness, concussion, and/or fatal head injuries will be produced. The Guide continues, "where possible, deformable structure and padding material should be considered to absorb the impact energy and to adequately distribute the forces over the face" (fig. D-5.9).

COMMENT: Effectiveness of padding has been accepted as being adequate for lesser thicknesses in commercial aircraft, which also have lower G criteria. There is also a question as to whether the same level of protection is needed for the extremities. From earlier Swearingen work, it was concluded that covering a head impact surface with 1 in. of Koreseal, (since superseded by Ensolite AH, or equivalent), would be considered to provide for delethalization.

SEAT CUSHIONS

Seat Cushions — General Requirements

Seat cushions should preclude body contact with seat structure while being light, tough (wear resistant), easily replaced, comfortable, and ventilated and provide flotation, while minimizing motion during crash loading and rebound after crash loading. For Army purposes, load limiting cushions were considered to be undesirable. Net-type cushions are usable if designed to limit maximum deformation and return movement, and to control potential for submarining or dynamic overshoot. Furniture type back cushions are acceptable; finally, a head rest should be provided to provide whiplash protection.

Direct contact surfaces of the seat bottom and seat back "should be designed for comfort and durability." However, "sufficient cushion thickness of the appropriate material stiffness should be provided to preclude body contact with the seat structure when subjected to either the specified operational or crash loads. ... The conflicting requirements of long-term comfort-versus-crash safety considerations have made this a difficult design area."

From comfort emphasis in the past, thick, soft cushions were used, spreading the load to avoid buttock pressure points. Holes or forced air flow (or net cushions) provided for cooling.

COMMENT: However, the softness of such cushions permits a velocity build-up as the soft material compresses farther. Build-up is rapid during initial loading then followed by a shorter stopping distance during the final stages of high deceleration loading — for a nonlinear stopping characteristic that puts major decelerations over a much shorter distance. In order to minimize
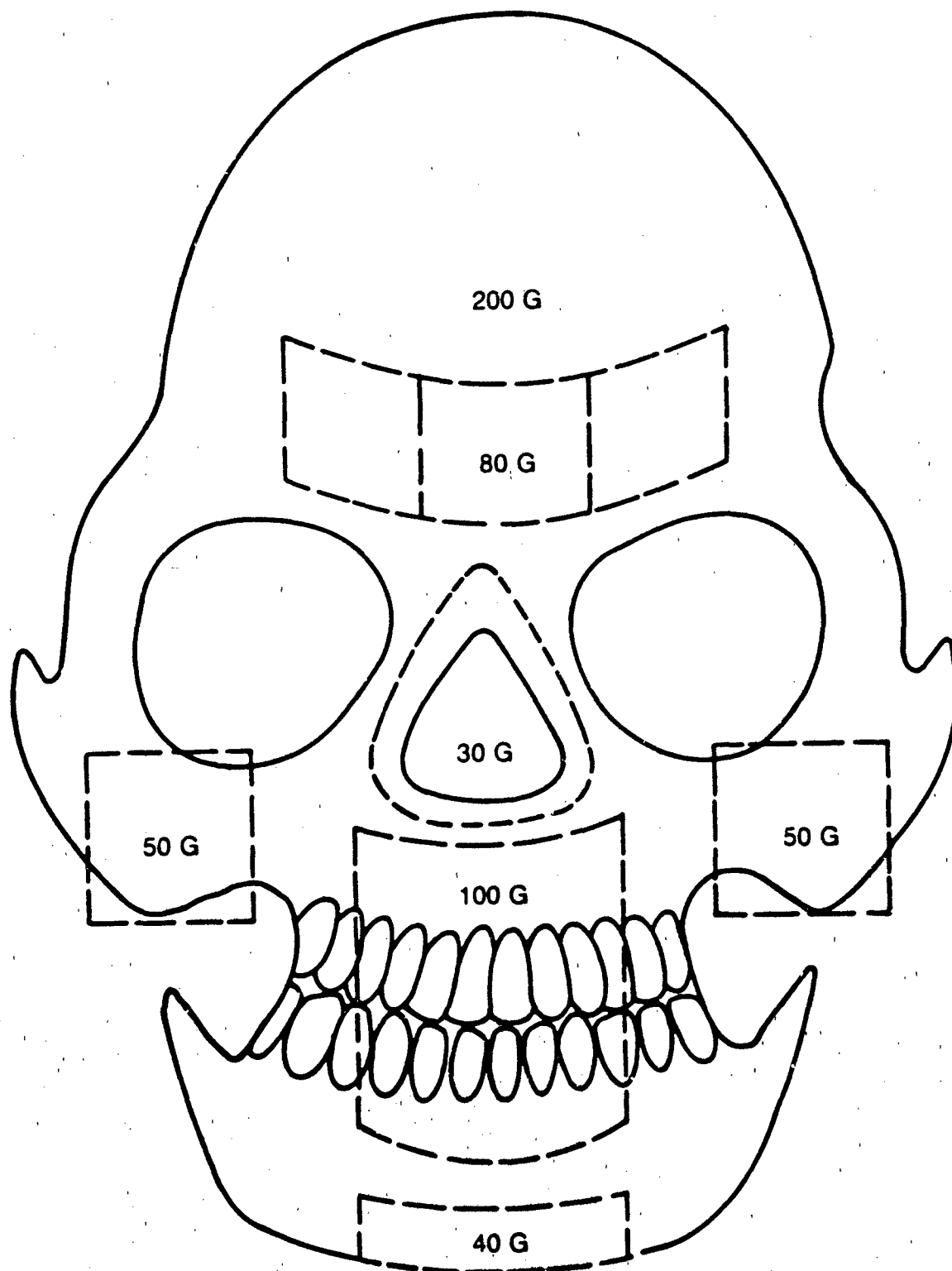
Figure D-5.9 – Summary of Maximum Tolerable Impact Forces on a Padded Deformable Surface (Swearingen, 1965)

such initial motion, crash safety considerations require a minimal thickness of soft foam. One approach uses a cushion base contour of a "universal" buttock configuration with foam layer(s) added. Rate-sensitive (conforming, but hard to sudden impact) foam can be used on top of the base to soften contact somewhat. For example, a thin layer of soft foam may be used on top for comfort material and permit cooling air motion.

According to the Guide, seats of light movable weight (less than 30 lb.) should use cushions for comfort only. Maximum uncompressed thickness should be 1.5 in. unless cushion design and material properties produce a beneficial result in reduced transmission of force. By Army criteria, the optimum seat cushion will:

1. Be extremely light weight

2. Possess flotation capabilities

3. Be nonflammable

4. Be nontoxic; will not give off fumes when burned, charred, or melted

5. Be tough and wear resistant

6. Be easily changeable

7. Provide comfort by distributing the load and reducing or eliminating load concentrations

8. Provide thermal comfort through ventilation

9. Provide little or no rebound under crash loading

10. Allow an absolute minimum of motion during crash loading

Energy Absorbing Cushions

Cushioning materials used to absorb energy include foams, honeycomb, and net-type cushions. "In most cases, the back cushions will not play a significant role in crash dynamics; however, it will influence comfort and can influence the injury tolerance of the spine." Lumbar supports are desirable; a lumbar support that holds the lumbar spine forward slightly increases tolerance to vertical spinal loads.

However, use of cushions per se as load limiters is undesirable. Resulting downward motion of the torso will produce added restraint harness slack (when it is desirable to minimize same). Also "a crushable cushion does not make optimum use of the available stroke distance," since crushing space is needed and cushions can be only 75% as efficient as a mechanical load limiter. They "are impractical in rotary and light fixed-wing aircraft because of the long stroke distance required to attenuate the high vertical loads" required by Army criteria.

HEADREST

A 1.5-in. headrest should be provided for occupant head/neck whiplash protection from backward flexure of the neck. "Cushioning can be provided by a thin pad and deformable headrest or a thicker cushion on a more rigid headrest." Results of the TARC study (ref. D-3) indicated that a less thick headrest would be desirable to accommodate a full range of male and female population.

TEST

Structural Subsystem Test Requirements

For Army systems, both static and dynamic tests of prototypes are recommended, including testing of seat and litter systems as complete units. Component testing is to be used wherever possible. Subsequently, tests are to include cushions in place, seats full up and full back (unless a more critical position exists) and normal floor buckling and warping conditions set up for the most critical impedance to seat stroking. Seat mounts should be actual aircraft hardware. Seat deformation should be measured as near the seat reference point as is possible. Subsequently, only quality assurance testing is necessary unless major structural changes occur. If desired, dynamic tests with loading in all principal directions may be substituted for static tests. In static test, both unidirectional and combined loading tests should be used, with test loads applied proportionately through a body block restrained in the seat by the restraint system. Multiple tests are specified, using the effective weight of the 95th percentile male for all but the downward loading, which uses the effective weight of the 50th percentile male. Multiple occupancy seats should be fully occupied when tested; additional tests should be accomplished for other adverse conditions that are identified.

The authors' discussion of static versus dynamic testing recommends that static tests be used because real time observation is possible, structural response information is more comparable to typically used static analyses, and tests are more economical. However, all U.S. Army prototype seats should be dynamically tested for two conditions, (1) downward at a 30° forward and sideward tilt and, (2) forward at a 30° side facing angle.

To reduce costs, special dynamic test conditions are permitted for seats having less than a 12-in. stroke. First, the costly full-scale crash test is considered desirable. However, and secondly, alternative dynamic testing of the seat only with a two stage pulse is acceptable, using a smaller initial G plateau representing failure of the gear and increasing to a later higher G plateau representing fuselage crushing. (Landing gear data to be based on results from drop test; fuselage properties are to be determined by the most comprehensive and rigorous analytical techniques, supported by test data).

Personnel Restraint Harness Testing

Army requirements include static and dynamic test of restraints along with the structure to which attached. Additionally, all components (webbing, tiedowns and hardware in the load path) as well as subassemblies should be statically tested separately to verify strength and elongation.

Head Impact Test Procedures

Head impact test procedures are most often to use a head form equipped with an accelerometer and to propel to impact with the surface to be evaluated via controlled drop, swing (pendulum) or ram.

Standard Test Methods for Energy Absorbing Foams

Among tests used from ASTM D 1564-71 (Standard Methods of Testing Flexible Cellular Materials — Slab Urethane Foam) are both load deflection and compression set. Numerous tests for various possible applications are defined. For "reasonable survival potential for head impacts as velocities up to 20 ft/sec with a padding thickness between 1.5 and 2.0 in. ..."acceleration of the head should not exceed 60 G and sufficient material must be crushed to reduce the head velocity from 20 ft/sec to 0 ft/sec in the process of absorbing the head kinetic energy of approximately 60 to 90 ft-lb."

Evaluation criteria for load distributing applications involves the assumptions that "A load distributing pad should permit the face to penetrate the surface easily, then maintain a cushioning layer of foam between the base and the underlying structure during collapse of the understructure." In terms of energy absorbing efficiency, Rusch (ref D-10) is cited as stating:

1. "Energy absorbing characteristics of a brittle foam are superior to those of a ductile foam,

2. "The optimum energy absorbing foam has a large cell size, a narrow cell size distribution, and minimum number of reinforcing membranes between the cells; and

3. "Foam composites offer no significant advantage over a single foam."

APPENDIX D-A

Two topics related to crash pulses are discussed herein. The discussion turns on the relationship $s = vT^*$, where v is the velocity content of the pulse (the pulse is assumed to stop an object with initial velocity v), T^* is the time coordinate of the centroid of the pulse, and s is the stopping distance. The above formula is convenient to apply since the centroids of standard pulse shapes (e.g., triangles, trapezoids, sinusoids) are tabulated in engineering handbooks. The relationship reduces the problem of solving the differential equations of motion to the simpler geometric problem of computing T^*.

The topics are: discussion of errors in the estimation $a = v^2/2s$, where a is the average pulse acceleration and v and s are as defined above; and a simplified method for computing energy absorber stroke requirements.

Before discussing the topics of interest the relationship $s = vT^*$ will be derived.

Derivation of $s = vT^*$

Let $s(t)$, $\dot{x}(t)$ and $\ddot{x}(t)$ denote the position, velocity and acceleration of the vehicle as functions of time. Assume that an acceleration pulse $x(t)$ of duration T is given. Further,

$$x(0) = 0, \quad x(T) = s, \quad \dot{x}(0) = v, \quad \dot{x}(T) = 0.$$

(i.e., the vehicle crashes with initial velocity v, coming to rest in time T and distance s). We can write from basic definitions:

$$\dot{x}(t) = v + \int_0^t \ddot{x}(\tau)d\tau \tag{1}$$

$$x(t) = \int_0^t \left(v + \int_0^{t'} \ddot{x}(\tau)\, d\tau \right) dt' \tag{2}$$

From equation (1),

$$\dot{x}(T) = 0 = v + \int_0^T \ddot{x}(\tau)d\tau, \text{ or}$$

$$\int_0^T \ddot{x}(\tau)\, d\tau = -v \tag{3}$$

Integration of equation (2) by parts and imposition of the requirement that $x(T) = s$ gives

$$x(T) = s = -\int_0^T t\, \ddot{x}(t)\, dt \tag{4}$$

Now define T* as the time coordinate of the centroid of the area under the deceleration curve — that is,

$$\left(T^* = \int_0^T t\,\ddot{x}(t)\,dt \middle/ \left(\int_0^T \ddot{x}(t)\,dt \right) \right. \tag{5}$$

Substitution of equations (3) and (4) into equation (5) gives

$$T^* = (-s)/(-v) = s/v. \qquad\qquad \text{Q.E.D.}$$

Errors in the estimation formula $a = v^2/2s$

If the crash impact velocity v and stopping distance s can be determined, the Guide recommends the following formula for estimating the average crash deceleration a;

$$a = -v^2/2s \tag{6}$$

If the crash pulse is in actuality skewed so that the majority of the acceleration occurs early in the crash, equation (6) overestimates the magnitude of a. To see why this is so, consider two aircraft crashes represented by the two triangular deceleration pulses shown in figure D-A.1. The pulses have the same average deceleration (v/T) as well as equal duration, equal magnitude, and equal area (the area represents the impact velocity v). The aircraft in the first crash will stop in a shorter distance (s) than the aircraft in the second, because the deceleration is applied more quickly. Thus, equation (1) would incorrectly predict a larger average deceleration for the first crash than for the second.

The correct relationship requires knowledge of the pulse shape. To derive the relationship, first note that the true average acceleration a is given by
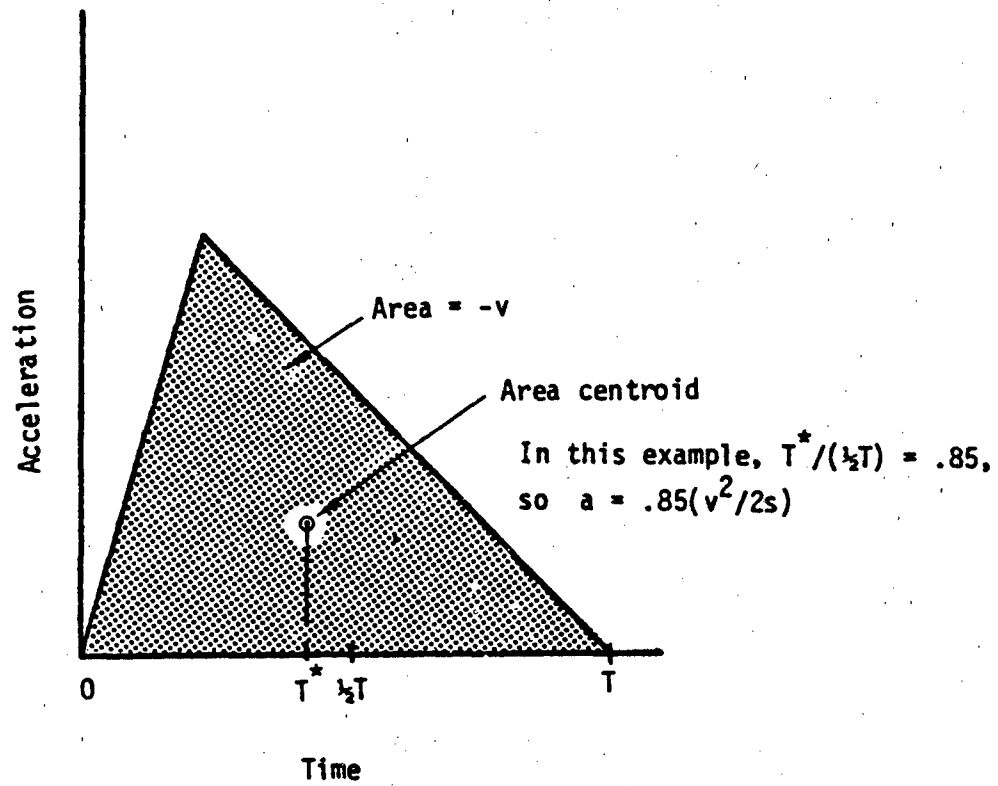
$$a = -v/T, \tag{7}$$

where T is the pulse duration.

The relationship

$$vT^*/s = 1$$

was derived in the preceding section. Thus

$$a = -(v/T)(1) = (v/T)(vT^*/s),$$

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Crash Pulse

In this example, $T^*/(\frac{1}{2}T) = .85$, so $a = .85(v^2/2s)$

which can be rearranged to read

$$a = - T^*/(T/2) (v^2/2s).$$

The implication is that when the deceleration pulse is shaped so that the majority of the deceleration occurs in the first half of the pulse, i.e., $T^* < T/2$, equation (6) overestimates the average deceleration a, while if most of the deceleration occurs in the second half, i.e., $T^* > T/2$, then equation (6) underestimates a. Equation (6) is accurate only when the centroid T^* occurs in mid-pulse — that is, when $T^* = T/2$. Figure D-A.2 illustrates equation (8).

Equation (8) can be used to bound the error in equation (6). For example, the centroid of a trapezoidal pulse of duration T must fall between (1/3)T and (2/3)T. Equation (8) shows that the maximum error inherent in equation (6) for a triangular or trapezoidal pulse is 33%, that is,

$$2/3(v^2/2s) \leq a \leq 4/3(v^2/2s).$$

Estimating Energy Absorber Stroke Requirements

The function of an energy absorber is to reduce the peak loads experienced by a passenger. As a result of energy absorber performance, the crash pulse experienced by the passenger has a different shape than the pulse at the floor. The difference in pulse shape causes a differential in stopping distance between the passenger and floor, which is achieved by deformation of the energy absorber and is termed the energy absorber stroke.

The energy absorber may be regarded as a filter which modifies the shape of the deceleration pulse. The stroke distance can be related to this filtering action in a simple, geometric way.
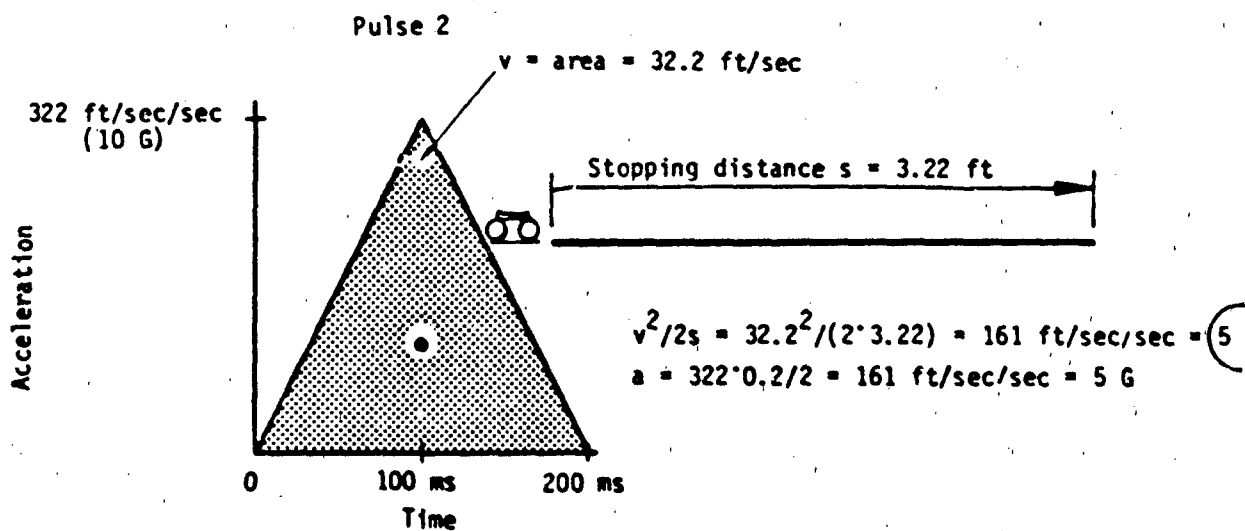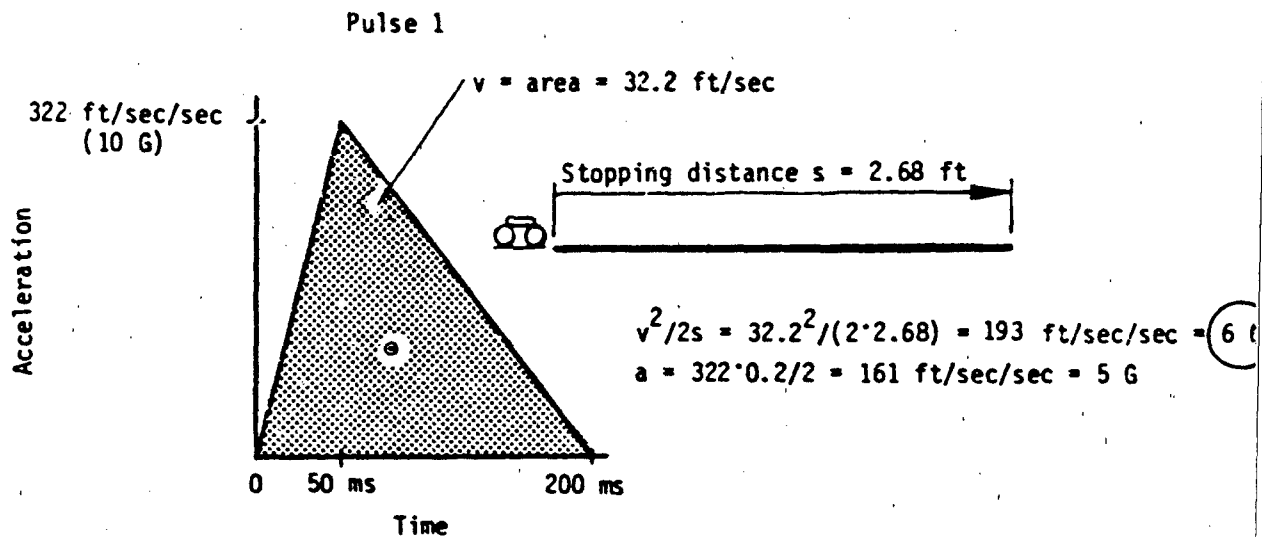
The stopping distance s is related to the pulse shape by the formula

$$s = vT^*$$

where v is the velocity at impact and T^* is the time coordinate of the centroid of the deceleration pulse. The energy absorber stroke requirement is

$$stroke = S_2 - S_1 = v(T_2^* - T_1^*) \tag{9}$$

where the subscripts 1 and 2 refer respectively to the floor and passenger. The required stroke is the initial velocity multiplied by the center of gravity shift caused by modification of the shape of the deceleration pulse.

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Pulse 1

322 ft/sec/sec (10 G)

Acceleration

v = area = 32.2 ft/sec

Stopping distance s = 2.68 ft

$v^2/2s = 32.2^2/(2 \cdot 2.68) = 193$ ft/sec/sec = 6 G

$a = 322 \cdot 0.2/2 = 161$ ft/sec/sec = 5 G

0   50 ms   200 ms

Time

Pulse 2

322 ft/sec/sec (10 G)

Acceleration

v = area = 32.2 ft/sec

Stopping distance s = 3.22 ft

$v^2/2s = 32.2^2/(2 \cdot 3.22) = 161$ ft/sec/sec = 5 G

$a = 322 \cdot 0.2/2 = 161$ ft/sec/sec = 5 G

0   100 ms   200 ms

Time

Equation (9) gives an intuitive view of energy absorber performance. For example, equation (9) can be applied to compute the stroke distance required by a simple load limiter under a triangular pulse (figure D-A.3). From geometric considerations,

$$v = at$$

$$vT_1^* = vt = at^2$$

$$vT_2^* = (2/3)kt(k^2at/2) + (kt + T/2) kaT \tag{10}$$

where T is calculated from

$$v = at = k^2at/2 + kaT \tag{11}$$

Equation (11) is used to eliminate T from equations (10), and the stroke is computed by subtracting equations (10). The formula,

$$\text{stroke} = vT_2^* - vT_1^* = at^2(k^3/24 + k/2 + 1/2k - 1). \tag{12}$$

is easily obtained. This derivation is simpler than the derivation in the Guide based on integration of the acceleration pulses.

SYMMETRIC FLOOR PULSE

cg SHIFT (ΔT°)

PASSENGER PULSE

SLOPE = a/t

ACCELERATION

TIME

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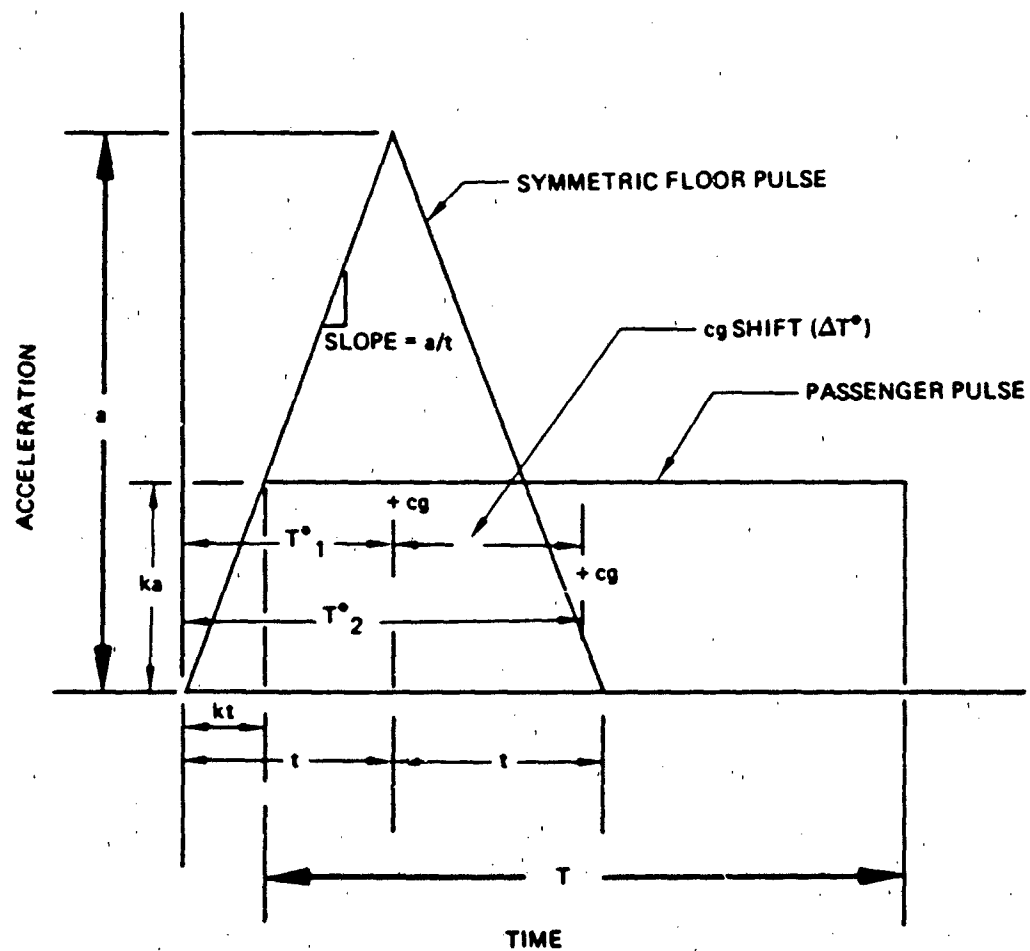
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15. Supplementary Notes

Final Report (Tasks I-IV)

16. Abstract

This report presents the results of a study to identify areas of research and approaches that may result in improved occupant survivability and crashworthiness of transport aircraft. This study was jointly sponsored by National Aeronautics and Space Agency (NASA) and the Federal Aviation Administration (FAA). The thrust of the study is the definition of areas of structural crashworthiness for transport aircraft which might form the basis for a NASA/FAA Research Program.

NASA and the FAA are planning a 10-year research and development program to improve the structural impact resistance of general aviation and commercial jet transport aircraft. As part of this program parallel studies have been conducted by The Lockheed California Company, The Douglas Aircraft Company, and The Boeing Commercial Airplane Company to review the accident experience of commercial transport aircraft, assess the accident performance of structural components and the status of impact resistance technology, and recommend areas of research and development for that 10-year plan. This report gives the results of the Boeing study.

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